Fermilab summer internship

Final Report

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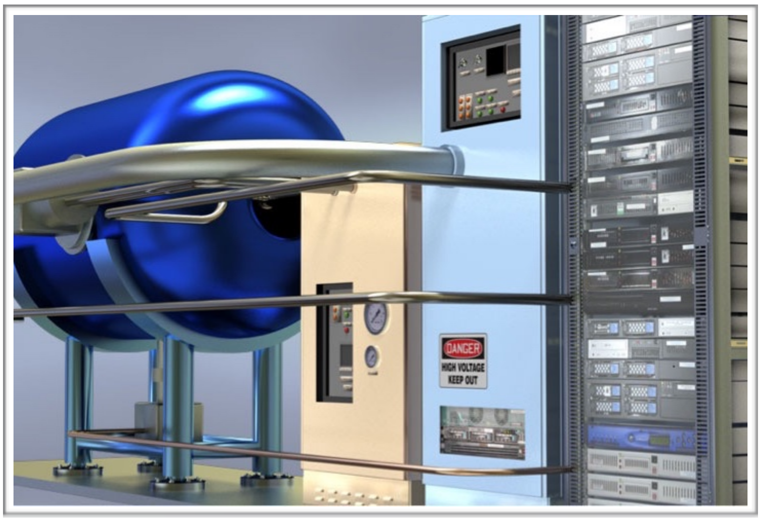
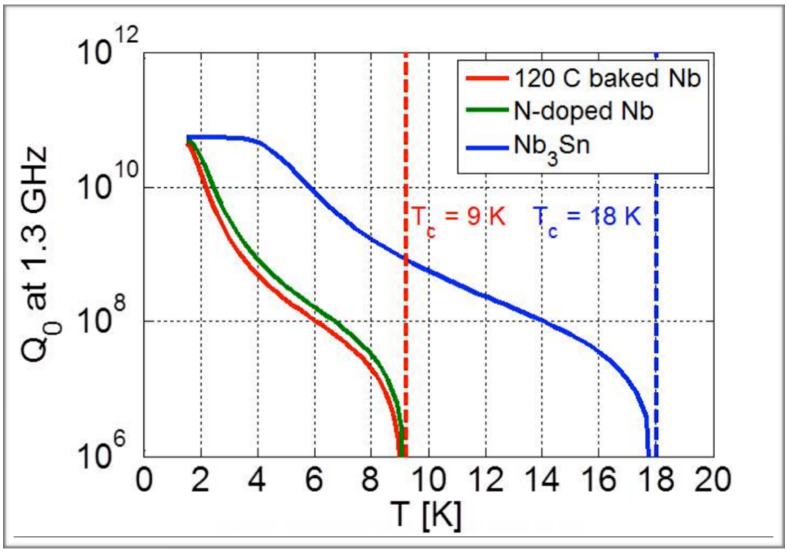
Introduction

During my summer internship at Fermilab I worked at the Illinois Accelerator Research Centre (IARC). At IARC, scientists and engineers from Fermilab, Argonne National Laboratory and Illinois universities work side by side with industrial partners to research and develop breakthroughs in accelerator science



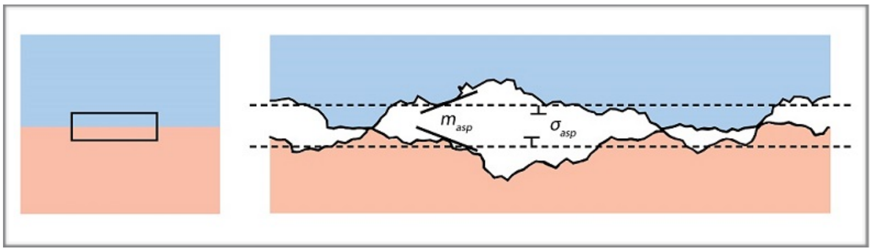
and translate them into applications for the nation's health, wealth and security.
One of the projects they are working on at IARC is the development of a design for a compact Superconducting Radio Frequency (SRF) high-average power electron linac. This innovative technology seems to be feasible exploiting recent advances in SRF cavities, Radio Frequency (RF) power sources as well as innovative solutions for the SRF gun and cathode system.
One of the most critical issues is the removal of the heat dissipated on the internal cavity surface. Nowadays, it is performed via liquid Helium cooling at temperatures near 2 K. This leads to complex, big and expensive external systems needed to compress and cool down the liquid Helium. One of the main goals for a compact and portable accelerator is thus to avoid liquid Helium cooling going towards a different kind of heat removal.

Recent technological breakthroughs based on Nb_3Sn coatings have enabled the creation of SRF single-cell 1.3 GHz cavities with quality factors that exceed $2*10^{10}$ at 4.5 K. A nine-cell cavity of this frequency operated at 10 MV/m and 4.5 K would require less than 5W of cryogenic refrigeration. This new technology allows avoidance of the low temperatures normally needed to have a high quality factor and needed also to avoid local quenching (loss of superconductivity on the cavity). And perhaps more importantly can eliminate the use of liquid Helium.



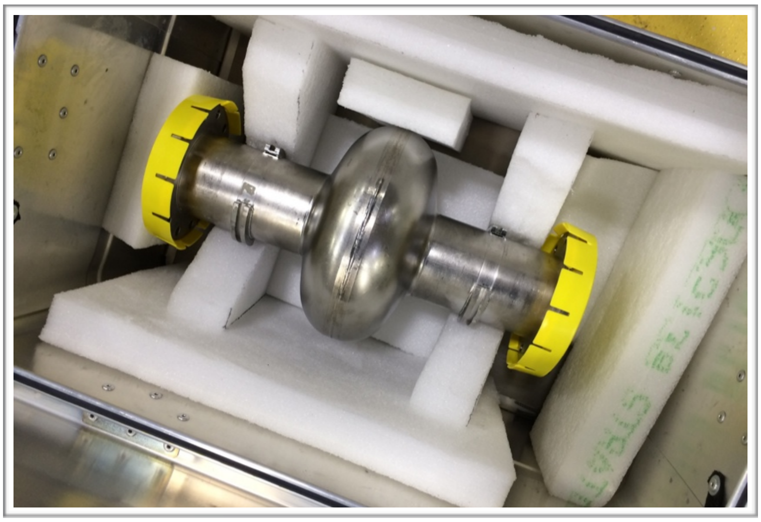
Further, the commercial availability of 5 W at 4.5 K cryocoolers have led to the possibility of thermal conduction cooling of this cavities through high purity Aluminum performed with a commercial cryocooler. The kind of cryocoolers we are dealing with are Gifford-McMahon (GM) coolers. They are based on a thermal cycle composed by two adiabatic (charging-discharging of the gas) and two isobaric (cooling-warming) cycles. They have a cold head with two stages at different temperatures, the first one higher (~60 K in our case) than the second one (~4.5 K in our application). The gas compressed and expanded in the close loop is Helium. Instead of having a liquid Helium bath, we can think on having a vacuum environment with a metal connection to the cold head, which contains quite a small amount of Helium in a close loop and in gaseous condition, which are all big advantages. Vacuum is needed in order to insulate thermally as far as possible the inside from the outside. The only type of heat transfer allowed in vacuum is radiative transfer; conduction transfer can only occur trough the supports of the internal structure that are necessarily connected to the outside.

The advantages of being able to use a commercial available technology like this kind of cryocoolers are remarkable, especially if the final goal is to make the accelerators available for a big number of buyers with different necessities.
However, this new cooling technique involves major difficulties in the study and the realization of the bond between Niobium and Aluminum. A lot of concern when dealing with heat transfer is about the so called thermal contact resistance. When two different objects are in touch, only a part of the real surfaces is in contact due to surface roughness. This results in an obstacle to the heat flowing from one domain to the other, and in the calculations this phenomena is treated as the presence of a resistance to the heat flow between the two surfaces, which is called indeed thermal contact resistance. The phenomena is highly complex, and a lot of environmental variables affect the value of the resistance measured. For this reason, an *a priori* estimate of the resistance is not easy, and in almost all the cases a preliminary experiment is needed in order to obtain a reasonable value of this parameter.
For this reason, the project “First test of conduction cooled SRF Cavity”



includes at the very beginning a series of preliminary tests aimed at estimating the contact resistance, in order to be able later to run realistic simulations of the temperature distribution along the cavity with different configurations of the connection between Niobium and Aluminum. After that, tests with a single-cell Niobium cavity heated with a resistor in the inside will be performed. The last kind of test will be done with a single-cell Niobium cavity excited with RF, simulating the actual working conditions. This last kind of tests will be repeated at the end with a Nb_3Sn coated cavity. Being more expensive and difficult to obtain, this last kind of cavities will be used only in the ultimate tests, when the experimental procedure is both well defined and well tried. The success of this series of experiment on single-cell cavities will lead to a new series of tests pointed towards the multi-cells cavities that are possibly going to be installed in the future portable accelerator.

The goal of my stay at Fermilab was to perform simulations (COMSOL software) of the conduction cooling, to set-up the experimental equipment for the tests and, at the end, to perform some of the first experiment needed to measure the thermal contact resistance.



Experiment set-up

The main components of the setup are:

- the cryovessel, or cryostat
- the cooling system
- the vacuum system
- the control and monitoring system

The cryovessel is a stainless steel vacuum vessel which reside inside a radiation shield which contains the items to be cooled and all the instrumentation needed for the cooling, heating and monitoring of the system.

From the outside of the cryovessel to the inside, the following layers and temperatures can be found:

- outside, ~300 K
- cryovessel
- vacuum space
- Multi-Layer Insulator (MLI)
- radiation shield, ~60 K
- vacuum space
- cavity or Niobium sheet, ~4.5 K

The MLI is made of 45 layers of a reflective plus an insulating foil. It wraps the lateral surface of the radiation shield in a spiral. After each rotation, one of the layers covering the bottom of the shield is attached to the layers on the lateral surface, so that it is like if each layer covering the bottom and the lateral surface were a single piece. To be able to remove the radiation shield without the necessity of recreating all the MLI each time, the top plate is separately coated.

Its 45 layers are taped all together to the outer layer of the lateral MLI, loosing in thermal traps but gaining in convenience and time before and after each test. The MLI is needed to reduce the thermal load on the first stage of the cold head. In fact, the heat entering from the external environment will find first of all a vacuum gap and then a great resistance because of the MLI, so only about 40 W of heat will reach the radiation shield. The heat that reaches the radiation shield is removed by the first stage of the cold head, as the radiation shield is directly connected to that. Essentially, the heat from the outside is all stopped by the radiation shield. Inside the radiation shield there is another vacuum gap and then the object to be cooled down, connected to the second stage of the cold head. So the second stage removes the heat produced inside the radiation shield and the little heat that goes trough the radiation shield and is irradiated in the inside of it.

Inside the vessel and connected to the top plate there is a lot of instrumentation useless for our purpose. The vessel is not a new item but it was used before in IB1, and even before at KEK in Japan for some experiments on the conduction cooling of magnets. That instrumentation is thus an inheritance of the magnet test setup.

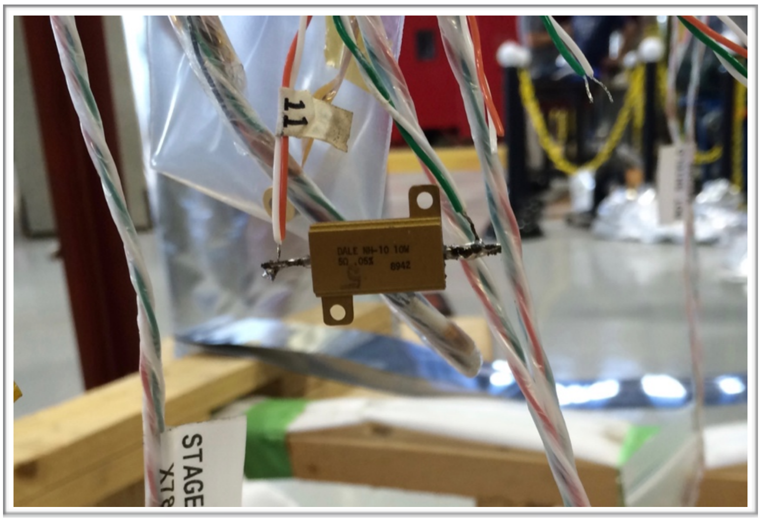
The cooling system includes the cryostat itself, a cryocooler and a chiller. The cryocooler has the following components: a Helium compressor, 2 m x 20 m long flexible hoses, and a cold head. Each component contains pressurized Helium of about 235 psig. The first stage of the cold head operates at ~60 K, the second stage at ~4.5 K. The chiller and the compressor are connected together by means of flexible hoses. The liquid that flows from the chiller to the

compressor is a 50/50 mixture of propylene and distilled water. The liquid temperature is approximately 15°C.
The first stage of the cold head is directly in touch with the radiation shield, whereas the second stage is connected to the cavity/Niobium sheet via an Aluminum connection. The optimization of the shape of the Aluminum connection for the cavity is one of the main goals of the study and of the simulations. A good connection must be simple and cheap to be produced, especially in view of the large-scale application. It also must minimize the total amount of Aluminum used and minimize the differences in temperature between the different parts of the cavity. Complying to the last criteria implies that the cooling is performed as close as possible to the zone where heat is produced, there are no zone cooled less than needed or more than needed, the material is used in the best way and that all the material behaves approximately at the same way. Hot spots have to be avoided as much as possible in order to lower the risk of having zones more likely to be subjected to a possible local quenching than the others.

The vacuum system is made of the vacuum vessel itself and two pumps that work in parallel. The two pumps working together are capable of lowering the pressure to 10^{-4} torr. The desired pressure (~10^{-7} torr) is reached only when the cryocooler is turned on.
Ten temperature sensors monitor the temperature inside the cryovessel. Two of them are Platinum RTDs, designed to work at a minimum of 14 K. They are placed one near the first stage of the cold head (~60 K), one on the bottom of the radiation shield (~60 K). The eight remaining are Cernox RTDs, designed

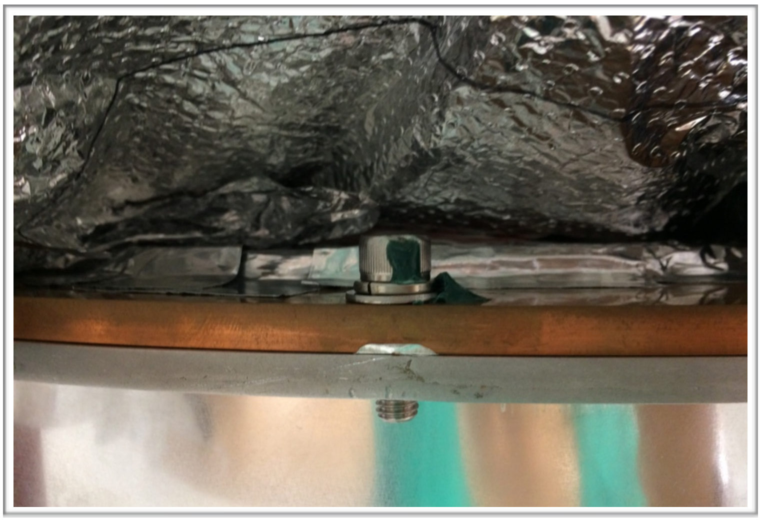
to have a high sensitivity from 2.0 K to 40 K. They are more precise that the first ones but also more expensive. They are placed on the second stage of the cold head (~4.5 K) and on the Niobium and Aluminum to cool down. Each of the ten sensors has four wires that are connected to the four 22-pins connectors on the top plate and, from there, by means of ten different cables, to the temperature readout (LakeShore Model 224). The temperature monitor reads the resistances of the wires and calculates the corresponding temperatures using the calibration curves inserted by the operator. The temperatures can be read and recorded with a custom LabView interface installed on the laptop used for the tests.

In the experiments about the thermal contact resistance, in order to heat up the Niobium piece, a 5 Ω resistor is installed. It is capable to reach 10 W. A manual laboratory DC power supply is used to regulate the voltage supply to the resistor.



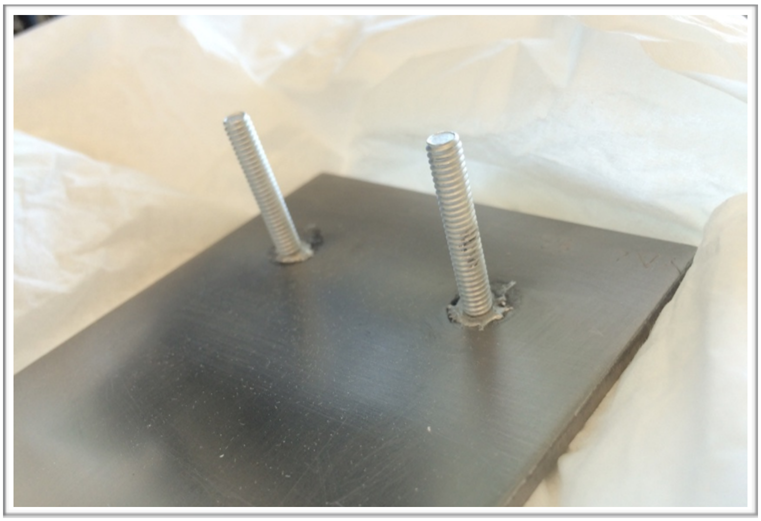
Working in a vacuum environment and working at cryogenic temperatures are two major issues in these experiments. Both these conditions make it difficult to maintain acceptable thermal connections. The vacuum environment implies that there is no gas inside the vessel, so thermal conduction can be accomplished only by conduction trough solids. It also means that every gap is an insulating layer. This creates a big issue also for the heater: attention has to be payed to have a good thermal contact between the resistor and the heated surface in order not to damage the resistor.

The fact that the experiment is performed at cryogenics temperatures implies that the materials shrink, and they all shrink differently related to their thermal expansion coefficient. So, when 4.5 K was reached, some surfaces that were in contact were not any more. The bolted connections conceived to transmit the heat between two different domains have to incorporate an Indium washer. Indium is very ductile at room temperature, so when it is squeezed between the two material by tightening the nut it adheres to the surface better that what Aluminum could do by itself, thus helping the thermal conduction by increasing the contact surface of the joint. Indium flows and diminishes in thickness, so the bolt may become loose.



For the two reason listed before the bolted connections must include an elastic element that supplies the wanted compressive force, so that the compressive pressure needed is assured even after the Indium has flown. Another method, used for example in the magnets experiments, is to epoxy the bolts. An issue related to the use of Indium is that it does not perform as well after a certain number of cooling and heating cycles, because it loses contact surface. For this reason this kind of interface can be used in the first experiments but it cannot result in a definitive configuration for the final commercial accelerator.
Another type of connection could be a melted interface, but the material surfaces have to be very clean and as smooth as possible and the melting has to be performed in a vacuum and clean environment: the goal is to have as little oxides, gases and impurities as possible in between the Niobium and the Aluminum interface, in order to minimize the thermal contact resistance. But the quality of the surfaces and the environmental conditions needed are not so easy to obtain and there are very few facilities capable of this kind of process that are available to us. One of the configurations of the connection between Niobium and Aluminum requires the stud-welding of studs on the Niobium

surface. Some analysis performed on the welded interface show that there are large voids in the Aluminum close to the circumference of the welding region, that compromise a lot both the mechanical strength of the joint, both its capacity of transmitting heat. In addition, the Aluminum of the stud is not high purity Aluminum in order for it to have good mechanical characteristics.

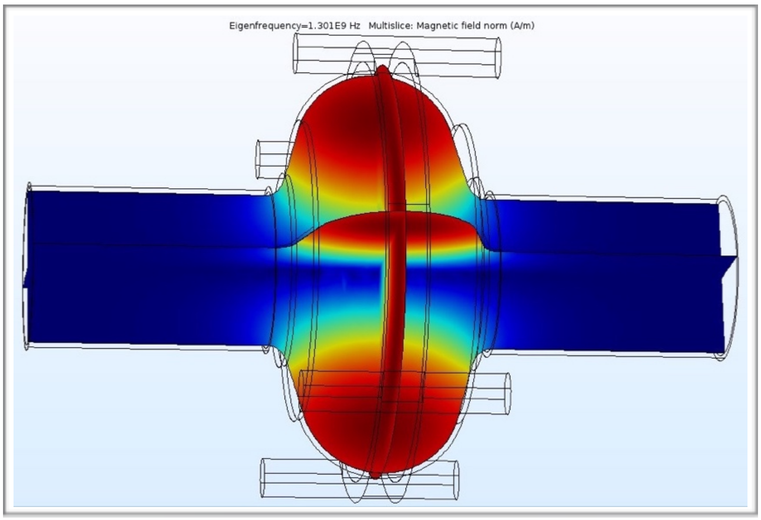


For these reasons, when simulating the Aluminum-Niobium connection configuration obtained with the studs welded to the equator of the cavity, the Aluminum studs are essentially not considered as a good thermal bridge between the Niobium and the Aluminum strip.
Both the Niobium and Aluminum surfaces are cleaned up before putting them in thermal contact between each other and with the heater and the cold head.
This said, the focus was mainly pointed to four different kinds of Niobium-Aluminum connections and to some hybrid combination of them. In the section "Simulations" a deeper analysis of the configurations considered can be found.

Simulations

The main goal of the simulations is to demonstrate the theoretical feasibility of the conduction cooling of the cavity and, after that, the exploration of different geometries for the Aluminum connection that can be used to cool down the cavity.

A big amount of attention has been paid to the thermal conduction resistance issue, and a realistic estimate of that parameter will be found only after the first experiments pointed towards its measurement.



Description of the model:

Some hypothesis are made before running the simulations.

First of all, the cavity is supposed to be run at 10 MV/m.

The E_{pk}/E_{acc} of the cavity is estimated to be $E_{pk}/E_{acc} = 2$. E_{pk} stands for the peak surface electric field, E_{acc} for the average accelerating electric field.

The surface resistance of Niobium is estimated to be $R_s = 20\ n\Omega$. Some simulations were performed with different values ($R_s = 10\ n\Omega$, $R_s = 40\ n\Omega$), but the most appropriate for a reasonable overestimation seems to be $R_s = 20\ n\Omega$.

The power dissipated locally is calculated with the following formula: $P_{diss} = 1/2*R_s*H^2$.

Where H is the magnetic field norm.

The first step of each simulation is the calculation of the electric and magnetic field inside the cavity. The second step is, knowing the magnetic field inside and so knowing the power dissipated, running the heat transfer simulation. The first step involves the calculations of the frequency of the cavity, which is determined

by the geometry of the cavity itself, and this is done calculating the eigenvalues of the electromagnetic field inside it.
When COMSOL computes the eigenvalues it uses an arbitrary scaling factor, so there is the need to reconnect the values calculated in the simulation to the reality of our tests. A normalization of the values given by COMSOL is done supposing a linear relationship between E and H, where E stands for the electric field norm.
The first step for the normalization is getting the maximum of the surface electric field calculated by COMSOL in the first step of the study (Step 1: Eigenfrequency).
$E_{pkCOMSOL}$=maxop1(emw.normE)
Where emv.normE is the norm of the electric field calculated by COMSOL and maxop1(*) is the operator that computes the maximum of an expression on the selected domain (in this case the internal surface of the cavity).
The second step is, supposing $E_{pk}/E_{acc} = 2$, the calculation of the average accelerating electric field relative to the COMSOL simulation.
$E_{accCOMSOL}=E_{pkCOMSOL}*(E_{pk}/E_{acc})^{-1}$
Then, the ratio between the E_{acc} at which the cavity is run (10 MV/m) and the $E_{accCOMSOL}$ relative to the COMSOL simulation is used to scale the magnetic field, which is necessary in order to calculate the power dissipated (remember the supposition that E and H have a linear dependence).
$c=E_{acc}/ E_{accCOMSOL}$
So the formula used to calculate the power dissipated becomes:
$P_{diss}=1/2*R_s*(c*\text{emv.normH})^2$
Where emv.normH is the norm of the magnetic field calculated by COMSOL.
The maximum temperature jump between the Niobium and the Aluminum surfaces considered acceptable is $\Delta T = 0.2\ K \div 0.3\ K$.
The mesh size used for the first trial of each calculation is “finer”. For more accurate calculations “extra fine”, “extremely fine” and some user defined meshes are also used. It will be shown in the section “Simulations results” that the values calculated with “finer” are close to the ones calculated with “extra fine” and “extremely fine”, and this justifies the use of a larger mesh, that reduces dramatically the amount of time needed for each simulation.
The different geometries used in the simulations will be illustrated when describing the simulation results. Mainly four different configurations of the Aluminum connection are used, with some variations for some of them.

Material properties:

For the material properties these are the values used:

- thermal conductivity of Aluminum: k_{Al} = 200 W/(m*K), k_{Al} = 1000 W/(m*K) or k_{Al} = 5000 W/(m*K).
- thermal conductivity of Niobium: k_{Nb} = 100 W/(m*K).

Boundary conditions:

As the cavity is in a vacuum environment, a first try is to suppose that the external surface of the cavity is thermally insulated.

-n*q = 0

Where the bold letters are vectors, **n** is the unity vector normal to the surface in each point, **q** is the heat flux vector.

The inside surface is heated due to the RF losses.

-n*q=P_{diss}

The surfaces of the Aluminum connection to the cold head are supposed to be at 4.5 K.

T=4.5K

In few test the contact resistance between Aluminum and Niobium is not included in the simulation. This was done in the very first test to see how the modification of single parameters changed the heat transfer, without focusing too much on the real phenomena, and in some simulations in order to see how looks like the best that could be obtained from an ideal joint.

In all the other cases the thermal contact resistance between the Niobium surface and the Aluminum surface is simulated. The value of this contact resistance at the beginning was estimated to be R_s = 100 cm^2*K/W, R_s = 50 cm^2*K/W or R_s = 35 cm^2*K/W, independently from the type of bound. (Sorry if the symbol used is the same as the one used to indicate the surface resistance of the Niobium cavity, the difference in the units should make it clear which one of them is used each time). After the experiment a reference value for the contact resistance will be found.

In order to simulate the contact resistance, COMSOL “thin layer” function has been used. Setting the layer thermal conductivity constant to 0.1 W/(m*K), the layer thickness has been changed every time in order to obtain the different resistances needed (1 mm, 0.5 mm and 0.35 mm).

Simulations results:

The first simulations are focused on the main material properties, as k_{Al}, R_s and contact resistance maintaining the shape of the Aluminum connection as a fixed reference. The following simulations are focused on the optimization of the shape of the connection. A big issue is the thermal contact resistance. At the very beginning some values for this parameter were supposed, but changing the shape of the contact there were some problems like jumps in temperature bigger than was expected. For this reason, the last simulations before the experiment was performed were run without any contact resistance, in order to compare the best case we could have with each configuration. After the experimental results, the new value found for this parameter will be incorporated in the new simulations.

k_{Al} modification

08_18_1.mph:

R_s= 20 nΩ

No contact resistance

Varying k_{Al} it can be seen that the maximum temperatures do not vary too much.

k_{Al} = 200 W/(m*K) --> T_{max}=4.70K

k_{Al} = 1000 W/(m*K) --> T_{max}=4.60K

k_{Al} = 5000 W/(m*K) --> T_{max}=4.58K

R_s modification08_18_2.mph:

R_s= 40 nΩ

No contact resistance

k_{Al} = 200 W/(m*K)

T_{max}=4.91K

It seems that to assume R_s= 40 nΩ is too much: the power dissipated results to be P_{diss}=1.62W, whereas the expected value is close to P_{diss}=0.5W.

R_s= 40 nΩ --> P_{diss}=1.62W

R_s= 20 nΩ --> P_{diss}=0.81W

R_s= 10 nΩ --> P_{diss}=0.41W

R_s, contact resistance modification

08_18_3.mph:

A contact resistance is included in the simulation: R_s = 100 cm^2*K/W.
R_s = 20 nΩ and k_{Al} = 1000 W/(m*K) --> ΔT=0.62K, T_{max}=5.21K
R_s = 10 nΩ and k_{Al} = 5000 W/(m*K) --> ΔT=0.30K, T_{max}=4.85K
Even with the best materials and internal surface roughness we cannot accept such a big contact resistance: the temperature jump is too high.

08_18_4.mph:
A contact resistance is included in the simulation: R_s = 50 cm2*K/W.
R_s = 20 nΩ and k_{Al} = 1000 W/(m*K) --> ΔT=0.32K, T_{max}=4.91K
R_s = 40 nΩ and k_{Al} = 200 W/(m*K) --> ΔT=0.73K, T_{max}=5.55K
Considering mean material properties, R_s = 50 cm^2*K/W is close to be acceptable.
Considering the worst imaginable material properties, R_s = 50 cm^2*K/W is not acceptable.

08_18_5.mph:
The most reasonable acceptable value seems to be R_s = 35 cm2*K/W.
R_s= 20 nΩ and k_{Al} = 1000 W/(m*K) --> ΔT=0.23K, T_{max}=4.82K
It permits to have a ΔT as in the specifications with a certain confidence, as the materials parameters are chosen with a good margin with respect of what we expect the material to perform in reality.

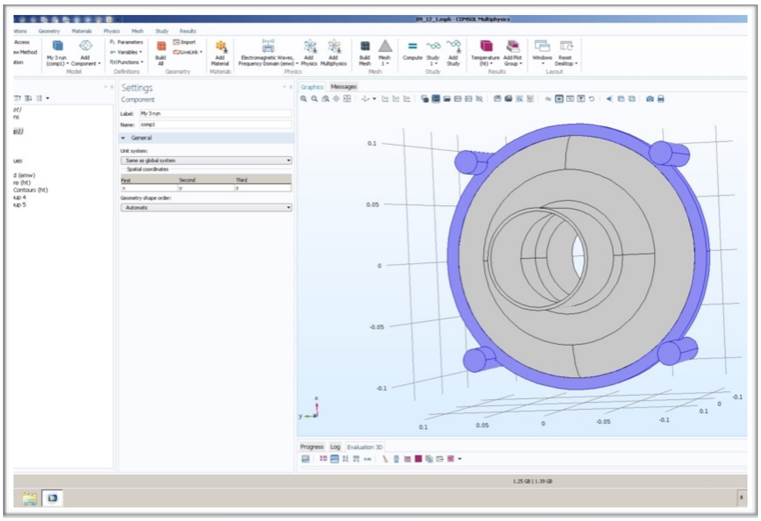
<u>Mesh dimension modification</u>
Only for simulations number 08_18_1.mph and 08_18_5.mph with R_s= 20 nΩ and k_{Al} = 1000 W/(m*K) the simulations were run with a finer mesh.

08_18_1.mph:
R_s= 20 nΩ
No contact resistance
k_{Al} = 1000 W/(m*K)
"Finer" --> T_{max}=4.60K
"Extra fine" --> T_{max}=4.61K
"Extremely fine" --> T_{max}=4.62K
User: max 0.005m --> T_{max}=4.62K
The results are convergent.
08_18_5.mph:

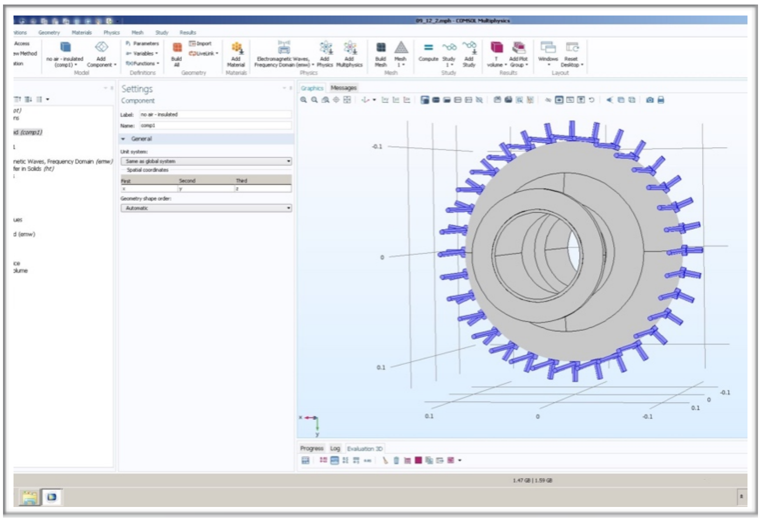
R_s= 20 nΩ
R_s = 35 cm^2*K/W
k_{Al} = 1000 W/(m*K)
"Finer" --> ΔT = 0.23 K, T_{max} = 4.82 K
"Extra fine" --> ΔT = 0.26 K, T_{max} = 4.86 K
"Extremely fine" --> ΔT = 0.26 K, T_{max} = 4.86 K
User: max 0.005 m --> ΔT = 0.26 K, T_{max} = 4.87 K
User: max 0.004 m --> ΔT = 0.25 K, T_{max} = 4.85 K
The simulations are convergent making the mesh finer. The result becomes accurate from the mesh size "extra fine".

<u>Geometry modification</u>

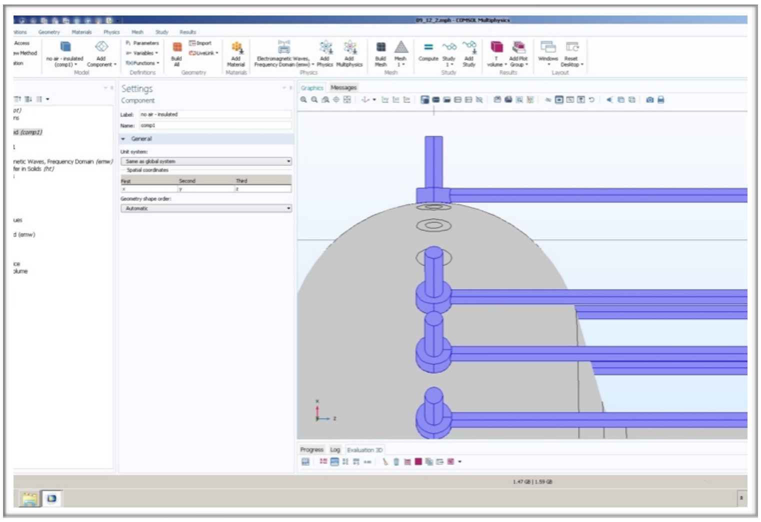
Mainly four different types of geometry were investigated. A few number of other geometries were simulated, but the results were not as interesting as the ones achieved with the following four.

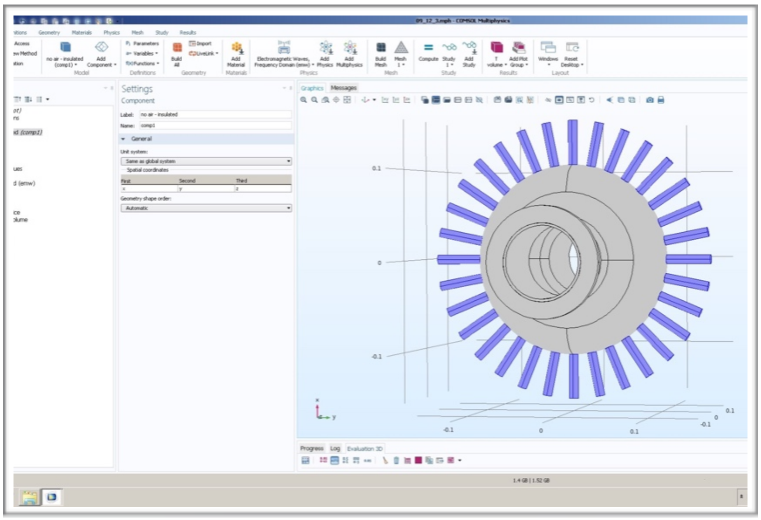


The first one (1) is an Aluminum ring that surrounds the equator of the cavity, connected with four axial (or radial) rods to the cryohead. It would be the best geometry for cooling the cavity, as the heat is removed symmetrically, from the equator, very close to the zone with the higher temperature, but its realization is very difficult to achieve in practical terms, due to the convexity of the surface near the equator, that makes it difficult to make the surfaces match.

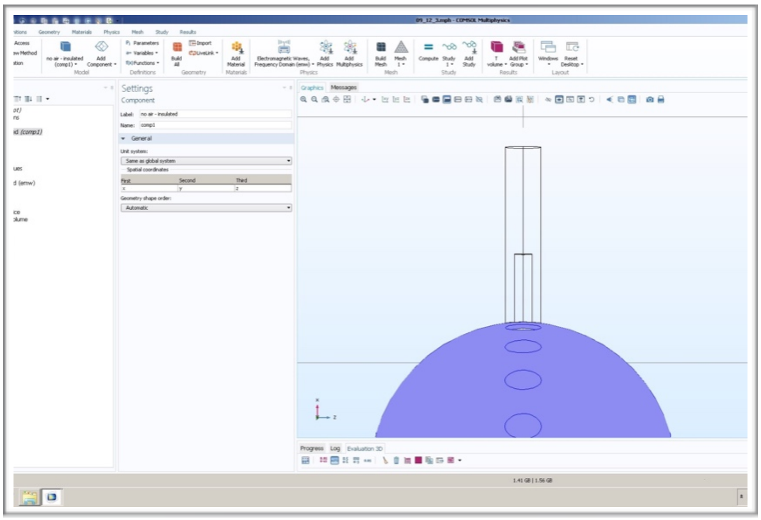


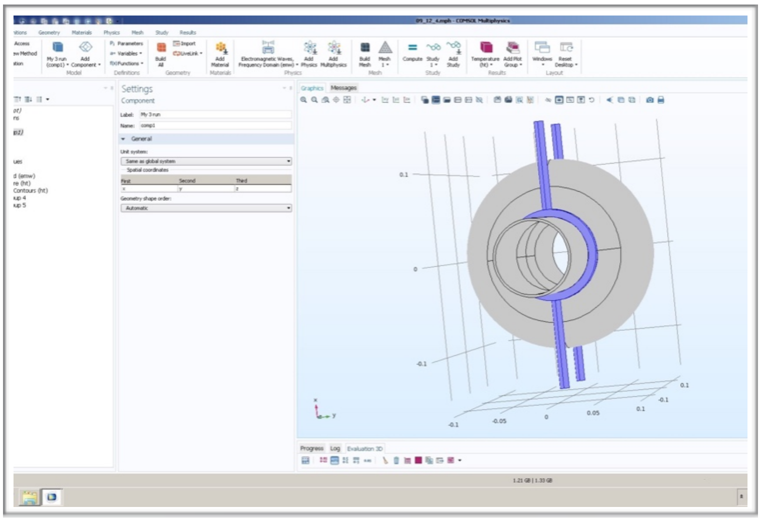
The second one (2) is made of a series of 8/16/32 studs welded to the equator of the cavity, which connect the cavity to the high purity Aluminum wires or leaves with an Indium washer, an elastic element and a nut. It cools the cavity from the equator as well as the first one, but the heat is removed from a discrete number of points, and as we increase the number of points the geometry gains in complexity. It is quite easy to produce (the complexity grows with the number of studs) but the great number of Aluminum wires or Aluminum leaves becomes an issue when dealing with a nine-cell cavity. Another issue is the presence of Indium: as discussed above, it would be better to avoid this metal if very few maintenance and a very high number of cycles between two servicing are desired.



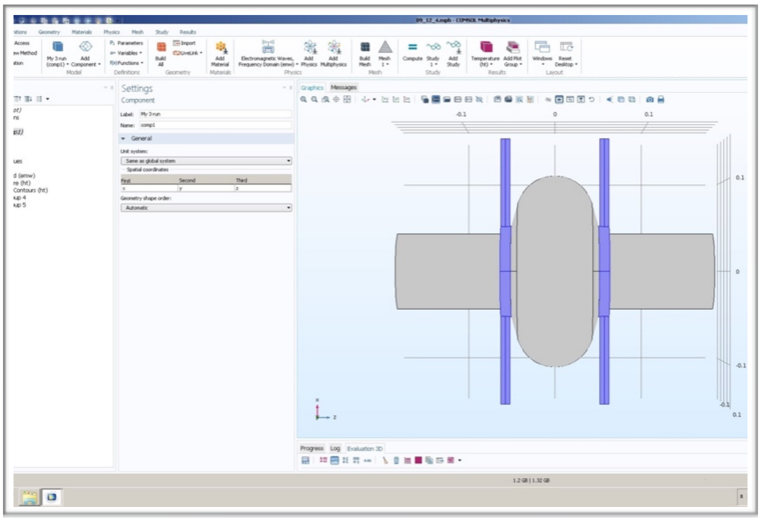


The third one (3) arises from the same base of studs of the second, but instead of having wires or leaves hold by a nut, it removes the heat radially with rods of high purity Aluminum directly screwed on the Aluminum bolt. Essentially, the (not high purity) Aluminum stud is needed for mechanical reasons, but it is not a good thermal conductor, whereas the high purity Aluminum rod has very poor mechanical properties but a very high thermal conduction coefficient.

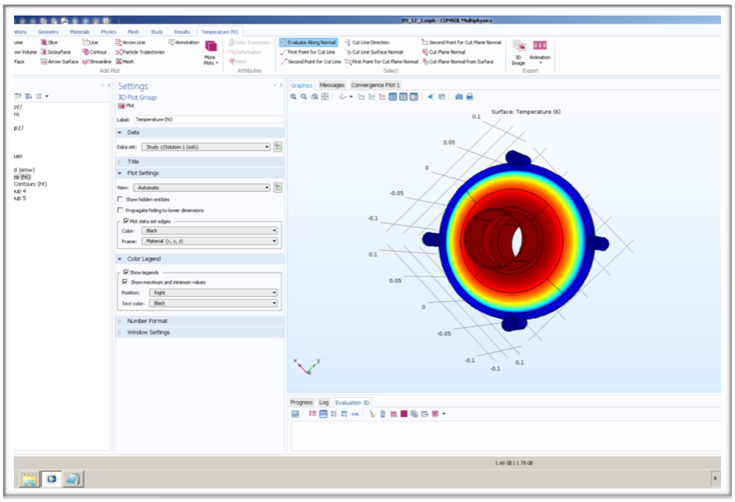




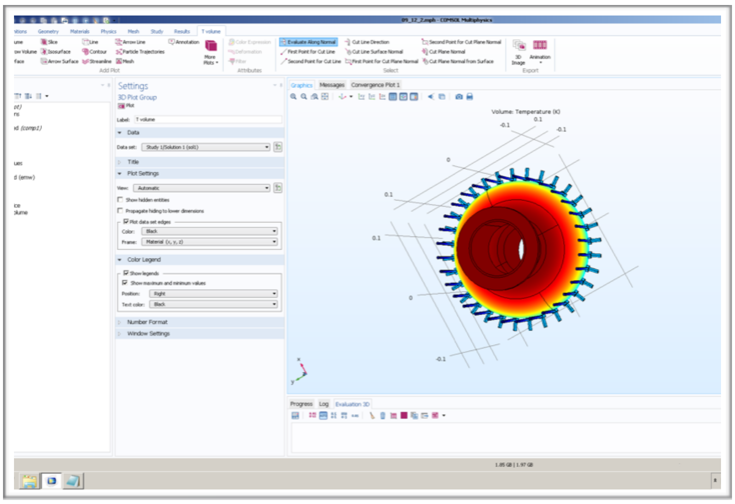
The fourth geometry (4) is made of two high purity Aluminum rings welded at the end of the cell with two radial rods that make the heat flow away. The heat is removed from the zone of junction of the cells, not from the best area, but it is a very simple concept, very easy to produce for a single-cell cavity, more difficult for a nine-cells cavity, and it involves a very few number of connectors between the cavities and the cryocooler.



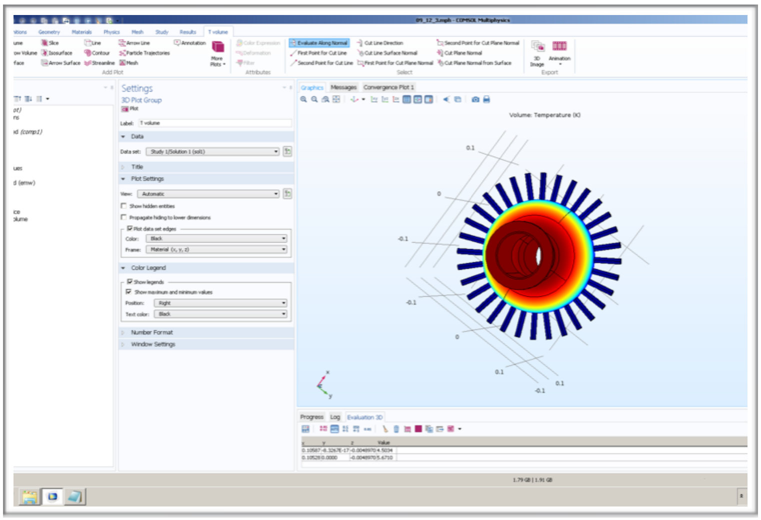
Simulations with and without thermal contact resistance were performed, results from the tests are waited in order to run new simulations with the parameters calculated from the real data. In fact, the thermal contact resistance used in the first simulations seems to be too high, so the results are almost meaningless.
For all the following simulations:
- k_{Al}= 5000 W/(m*K)
- R_s= 20 nΩ
- no contact resistance



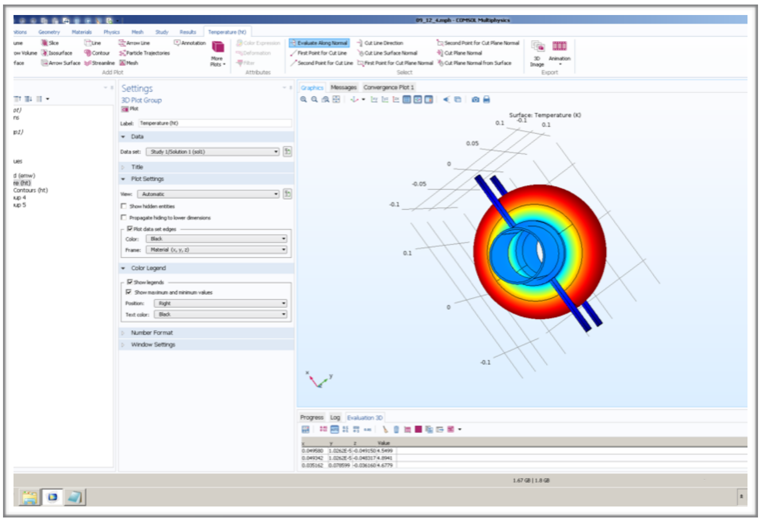
09_12_1.mph:
- geometry3.sat: Al ring on the equator, 4 connectors (1)
Max: 4.57K



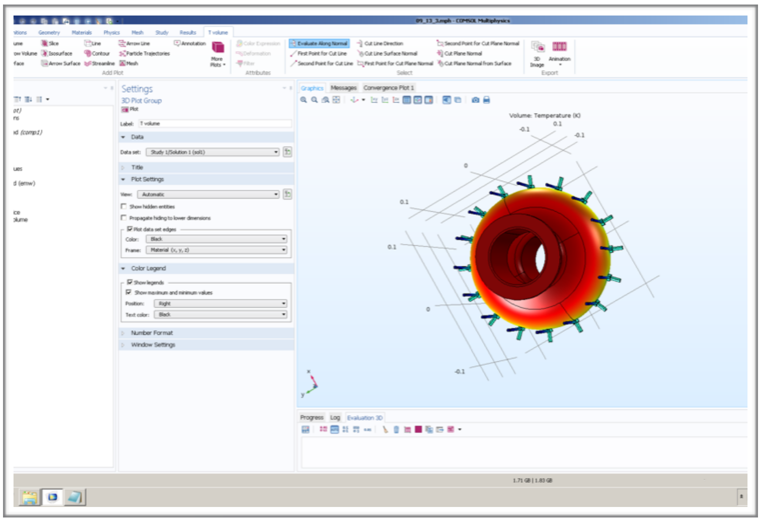
09_12_2.mph:
- geometry7.sat: 32 studs + wires (2a)
Max: 4.63K



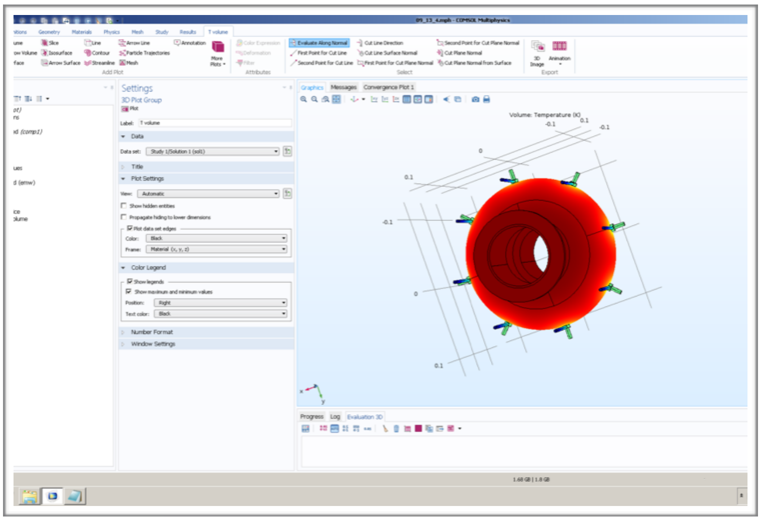
09_12_3.mph:
- geometry10.sat: 32 studs + rods (3)
Max: 4.59K



09_12_4.mph:
- geometry12.sat: Al rings on the connections, 4 connectors (4)
Max: 4.71K



09_13_3.mph:
- geometry6.sat: 16 studs + wires (2b)
Max: 4.69K



09_13_4.mph:
- geometry13.sat: 8 studs + wires (2c)
Max: 4.84K

Without any thermal contact resistance it seems that, from the best geometry to the worst one, the order is: (1), (3), (2a), (4). But, just for example, running some simulations with a contact resistance the order becomes immediately different: (1), (4), (3), (2a). This is because the contact areas between Niobium and Aluminum are very different depending on the connection, and the ratio between them can reach 7.

(1) Nb-Al contact area: 0.01338 m^2
(2a) Nb-Al contact area: 0.0025 m^2
(3) Nb-Al contact area: 0.001892 m^2
(4) Nb-Al contact area: 0.008939 m^2

For all the following simulations:
- k_{Al}= 5000 W/(m*K)
- R_s= 20 nΩ
- Contact resistance: 35 cm^2*K/W

09_09_1.mph:
- geometry3.sat: Al ring on the equator, 4 connectors (1)
T jump: 0.21K; Max: 4.78K

09_09_2.mph:
- geometry7.sat: 32 studs + wires (2a)
T jump: 1.18K; Max: 5.81K

09_09_3.mph:
- geometry10.sat: 32 studs + rods (3)
T jump: 1.17K; Max: 5.76K

09_09_4.mph:
- geometry12.sat:Al rings on the connections, 4 connectors (4)
T jump: 0.34K; Max: 5.05K

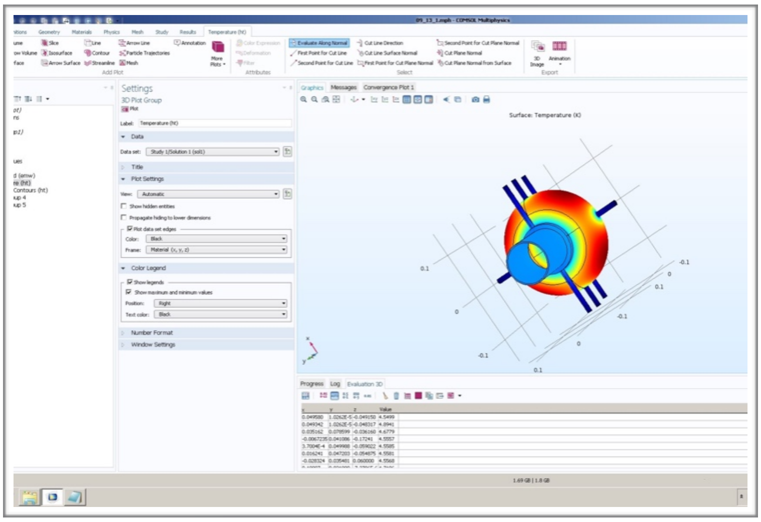
Conclusions:
Without any thermal contact resistance the geometries perform in a comparable way, whereas when adding a thermal contact resistance the differences in contact area and Aluminum volume start making a difference.
The simplicity of the connection is another important question to deal with. This becomes particularly important when thinking about the final commercial geometry, a nine-cell cavity that has to be cheap and has to require very little maintenance.

Geometry (1) would be theoretically the best way to cool the cavity, but it is not simple to implement. An optimization process should determine which are the minimum thickness, width and height of the Aluminum ring needed to achieved a good cooling of the cavity.

Geometry (2) is simpler to produce, but involves a lot of connections between the cavity and the cold head, which is unpractical and increases the number of possible failures. A deeper study should be performed in order to verify which is the maximum number of connection failures that can be considered acceptable and in which positions. An alternative to the use of Indium should be found for the final configuration that is going to be commercialized. The stud welding involves no heating of the inside of the surface, as it is a very quick process and the Niobium is a bad thermal conductor. This is a very good feature of this technique because the cavity that is going to be used will be coated with Nb_3Sn on the inside, and this coating is sensible to high temperatures.

Geometry (3) is more orderly than (2), does not involve Indium but is not so simple to produce as well.

Geometry (4) is the simpler to implement for a single-cell cavity, it becomes not so simple for a nine-cells cavity. It involves heating the side of the cavity at ~700°C, and removes the heat from a zone quite distant from where the maximum temperature is reached.

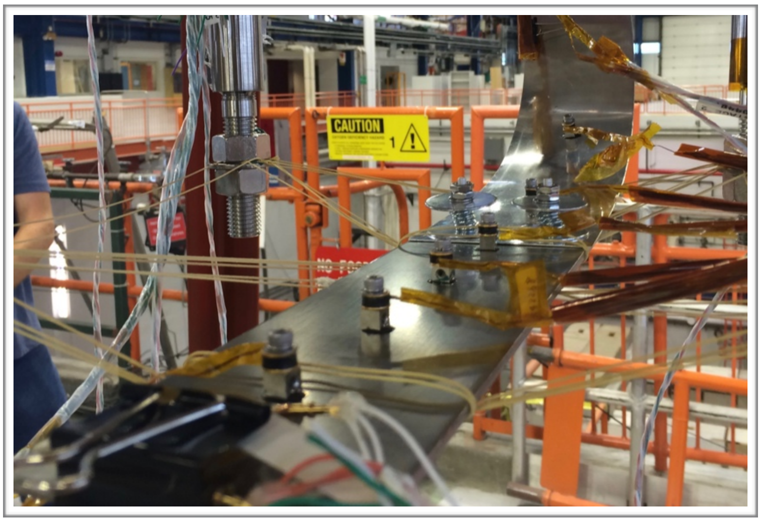


Some simulations were performed combining geometry (4) and (3), with four or eight studs, but a more accurate study is needed. It would combine the easy-to-do geometry (4) with the better position for cooling of the studs of geometry (3). It could mean that we could have less studs, which implies less connections to the cold head, with a lower maximum temperature because of the addition of (4).

The actual value of the contact resistance is difficult to be estimated *a priori*: the characteristics of the materials used, the roughness of the surfaces, the possible oxides present at the interface and the coupling method used lead to great differences in this value. The experimental results will give a reference number that will be included in the next simulations.

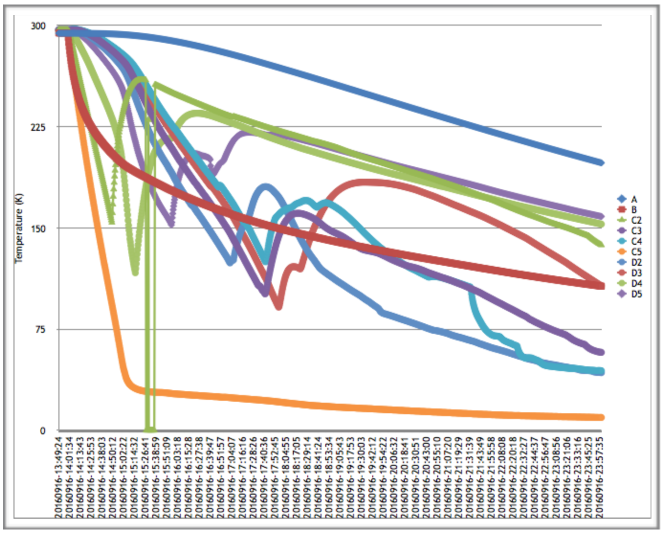
Test

The first test performed is a thermal contact resistance test. The aim of this test is to give an estimate of the thermal contact resistance, verify if the thermal conduction coefficients used in the simulations are close to reality and validate the simulation performed with COMSOL. If the simulations performed on this setup give results close to the ones measured in the tests, it is likely that also the tests on the cavities will measure results close to the simulations.



A rectangular strip of Niobium was connected to a thin high purity Aluminum sheet, which was connected to an Aluminum cylinder directly in touch with the cold head. On the Niobium sheet two Aluminum studs were stud-welded in order to create a connection with the high purity Aluminum sheet, whereas the Aluminum sheet was connected to the Aluminum cylinder by means of bolts. The cylinder was screwed to the cold head. In between all the surfaces in thermal contact there were Indium washers. The Niobium plate hanged from Kevlar wires connected to the internal sustains. The temperature sensors were taped to the sheets and some grease was put in between the surface and the sensor. The only one bolted was the one on the Aluminum cylinder of the cold head. Four sensors were positioned on the Niobium at equal distances from the others. Three were on the Aluminum sheet.

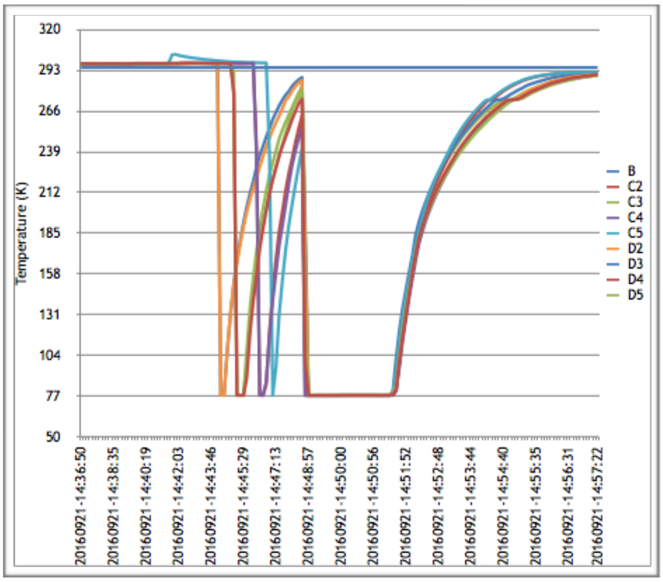
Unfortunately the chart time versus temperature of seven out of ten sensors displayed sharp jumps in temperature, so the sensors were considered untrustworthy and the test was aborted. Two of the sensors that worked were the Platinum RTDs, the other one was the Cernox RTD screwed on the cold head. As the sensors failed if and only if they were attached with the tape, the



main supposition was that this kind of connection did not perform properly. When the vessel was reopened the tape was found loose and the sensors did not look to be in contact with the metallic surface.

A test was done immersing all the sensors in liquid Nitrogen and checking if the temperature curves looked smooth in their way down to 77K. All the curves were smooth and all the sensors measured realtively the same temperature. So it was thought not to be a calibration issue, nor a malfunction of the sensors.

It the next test all the Cernox RTDs were attached to the metals with the same kind of connection of the one on the cold head. The one on the Aluminum closest to the second stage fell off before the test, to it was attached with a clip and some tape. Also attached was the heater.



In this case the curves looked smooth, but the sensors had a different cooling slope from what was expected, and very to 32 K the first inversion was seen:

some sensors supposed to be cooler than others started recording higher temperatures than the neighbors. At the end of the cooling, the order of the temperatures recorded was meaningless, and for that reason the sensors were considered unreliable again. A test with the heater was performed, and the temperature increases and drops were reasonably consistent with the distance the sensors had from the heater. Further analysis are needed in order to clarify the error in the temperature recording.