Novel RF Tuning Scheme for Jacketed Multi-Cell SRF Cavities using Pressurized Balloons

Supervisor: Donato Passarelli
Co-Supervisor: Mohamed Hassan
Fermi National Accelerator Laboratory
Technical Division

Marco Castellari
University of Ferrara

October 15, 2017

Contents

Abstract

SRF cavities have a huge impact in the particle accelerator science because of their ultra-low loss that extremely enhances their efficiency in accelerating particle beams. In the zoo of SRF cavities available, having different shapes and specifications, the attention of this project will be focused on multi-cell and high β cavities. The goal of the present project is to provide a solution for dressed SRF cavities that have field flatness issue of being lower than what is acceptable for cryomodule assembly. This helps to minimize the impact of a production failure in a large scale leading project such as PIP-II and LCLS-II from cost and scheduling standpoints. A tuning procedure for dressed multi-cell cavities capable of controlling the deformation of each single cell will be developed. Thus, we will have more control of the field flatness and final resonant frequency even for a dressed cavity. A mix of Finite Element Analyses and experimental tests will be performed to demonstrate the validity of the proposed approach and develop the full tuning procedure.

1 Introduction

Nowadays, particle accelerators are gaining always more importance and not only in the particle physics field, as it can be seen in [1]. The number of applications is increasing such as in medicine, nuclear energy, semiconductor industry and cleaning air and water. For this reason it is necessary to develop design technique that enhance the particle accelerator efficiency. In this project, the attention is focused on the linear particle accelerator based on Superconducting Radio Frequency (SRF) multi-cell cavities, that are the key technology for next-generation accelerators and future of particle physics. Cavities are one of the building block of a modern particle accelerator and these devices impart energy to the charged particles through a resonant electromagnetic field that builds up inside the cavity. In our scenario those cavities are composed by an array of single-gap resonators (i.e. 9 cells) and are made out of a superconducting material such as niobium, with a frequency of resonance of 1.3GHz. For more detail about the theory behind cavities see [2]. The cavities are then "dressed" with a vessel and sit inside the cryomodules that allow to cool the cavities to near absolute zero. The ultra-cold temperature allow the SRF cavities to conduct electric current with almost no loss of energy, meaning that nearly all of the electrical energy goes into accelerating the beam.

In order to have the highest performance of the entire particle accelerator, it is crucial to keep the SRF cavity at the exact frequency of resonance and have the highest field flatness possible. An SRF cavity is characterized not only by these two parameters but them are the most important for the aim of this project.

As it as been said before, on one hand, the resonant frequency is one of the most important parameters for SRF cavities and it is not possible to have arbitrary precision since the firsts manufacturing steps. For this reason the frequency of resonance can be changed both when the cavity is in operation by deforming the shape in the linear-elastic regime of niobium, preventing plastic deformation, or when the cavity is not under operation by an inelastic tuning procedure. The second way to change the frequency of resonance is the one we are interested to investigate in this project. On the other hand, the field flatness has a great importance for SRF cavities because it is an indicator of the accelerating gradient that can be reached. The field flatness, instead, represent the flatness of the electromagnetic field in the cells of the cavity, or rather, how much the field amplitude of the cells is close to each other, as it can be seen in Figure 1, and it is defined as $\mathrm{FF} = \frac{\mathrm{E}_{min}}{\mathrm{E}_{max}}$

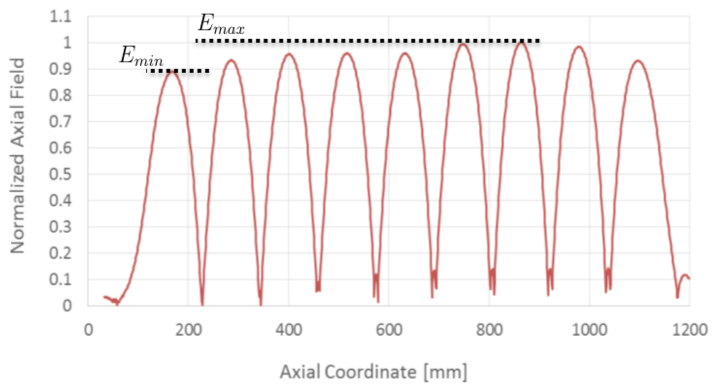


Figure 1: Field flatness

Indeed, have equal amplitude in cells is important to obtain the desired accelerating gradient. To match the target it is necessary to reach, at least, a field flatness greater than 90%.

In order to have cavities matching the targeted resonant frequency in operation (at 2K and in vacuum), adjustments to the shape are necessary from the early stages of manufacturing until the cavity is placed into the cryomodule. The necessity of adjusting the frequency of a SRF cavity after the manufacturing is due to the fact that actual manufacturing process cannot guarantee the grade of precision required for both resonance frequency and field flatness. Moreover, other preparation steps such as etching and heat treatments cause frequency shifts and field flatness deterioration that need to be compensated for.

Anyway, it is necessary to point out that there is an enormous difference in the effort in tuning a bare cavity or a dressed one. In the first hand, a bare cavity is easy to tune because the cells are fully accessible from outside but on the other hand when the cavity is dressed the tuning problem became harder. Till now, the technique to adjust both the parameters is to remove the vessel, tune the cavity and weld a new helium tank outside the cavity. Anyway this procedure is not plain and the welding can change the frequency of resonance.

This problem and the cost of the latter tuning technique lead to the development of a new tuning procedure, as the balloon tuning technique, in order to develop an inexpensive and faster tuning procedure for dressed cavities.

Outline The development of this novel technique started last year under the supervision of Donato Passarelli, Mohamed Hassan and Alessandro Tesi. The work that has been done by me, laid its basis upon the design of the balloons and the firsts tests about the possibility to effectively stretch a single-cell cavity. In order to theoretically and experimentally validate this technique I conducted various finite element simulations employing COMSOL to demonstrate the validity of the concept. Then, I developed the test set-up, in collaboration with Mohamed Hassan, and I fixed the cavity TB9AES018 for the LCLS-II experiment as a proof of the validity of the balloon tuning technique.

The remainder of this report is organized as follows. Section 2 gives account of the new tuning technique that is under investigation, then Sections 3 and 4 describe the tuning procedure in the details. In Section 5 are presented the simulations using COMSOL Multiphysics and the results are described in Section 6. Finally, Section 7 gives the conclusions.

2 A novel approach

From the first step of manufacturing till the moment the cavity will be mounted in the accelerator, some steps of tuning are needed. This is necessary because it is not possible to have the desired tolerance in each manufacturing step. The first operation of tuning is done when the cavity is "bare", or rather when there is not the helium tank outside the cells and so it is possible to act directly on the single cell, as it can be see in Figure 2, and it is possible to get a fine tuning both in frequency of resonance and in field flatness.

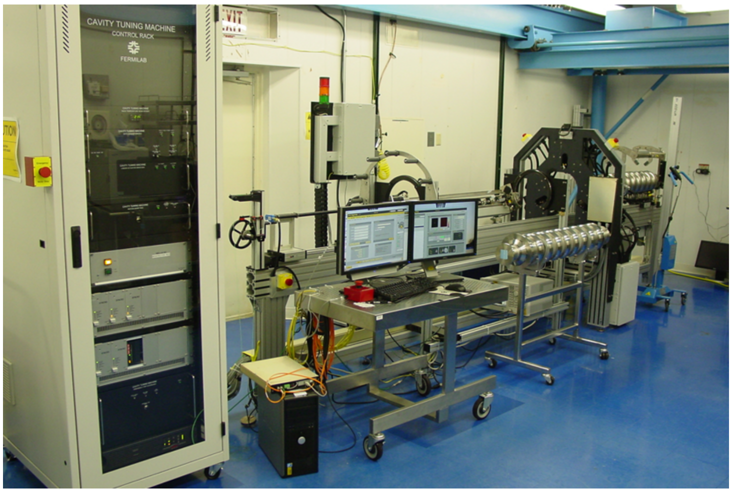


Figure 2: Automatic tuning machine (Courtesy: Fermilab)

The next step after the tuning of the bare cavity is to weld the helium tank and in theory, the frequency and field flatness of a cavity should not change during the welding. Thus, adjusting the bare cavity before welding the tank should be enough to fulfill the requirements when the cavity is dressed. Unfortunately, the reality is different and the welding is not the only one cause of detuning but there are many more unexpected causes (i.e. improper handling, improper cavity supporting, cavity overloading, etc.) that can produce unwanted permanent deformation of the cells which lead to have, in most cases, resonant frequency and field flatness out of specifications. Projects such as XFEL and LCLS-II have already experienced these accidents. To date when a dressed cavity is qualified from all aspects except field flatness, the possible solution to recover the cavity is to remove the outermost vessel (back to bare cavity), fix the frequency and field flatness by the existing tuning machine and after that weld a new helium tank around the cavity. It is clear that the amount of risks and costs on adopting this solution has negative impact on the budget and the schedule of important large scale projects.

The intent of the project is to develop a non-invasive and non-destructive setup that would help to remedy the accidental cases of dressed multi-cell cavities with field flatness out of specification. Developing such a tuning technique is crucial for the projects Fermilab is currently involved in. It will also impact the entire know-how of manufacturing and qualifying multi-cell SRF cavities.

The proposed method relies on pressurizing balloons inside the cavity to lower than a Maximum Allowable Working Pressure (MAWP) and mechanically applying compression or traction force on the end flange, using existing mechanical tuner devices. The differential pressurization causes higher stresses in a targeted cell, which lead to plastically deform it. As a consequence the iris-to-iris distance (Figure 3) of the cell permanently changes, shifting the resonant frequency and adjusting the field amplitude inside the cell.

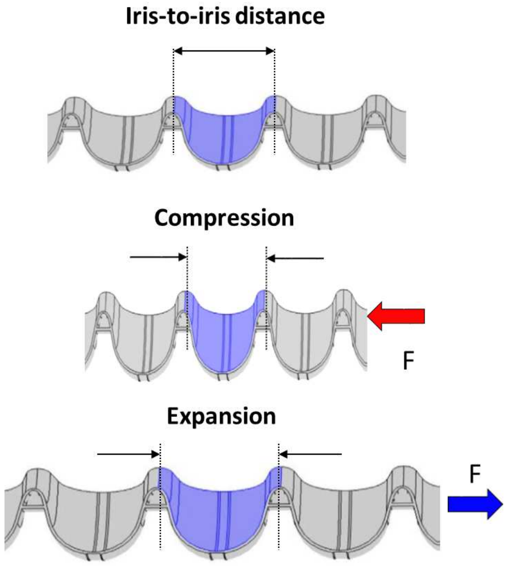


Figure 3: Iris-to-iris distance variations of a multi-cell cavity

The main features of the Balloon Tuning Technique are:

- the possibility to control the deformation of each cell independently from each other cells
- the field flatness and the resonant frequency can be improved acting only on the targeted cells
- it is inexpensive if compared with the already existing technique that imply to remove the vessel, fix the cavity and weld a new helium tank around the cavity
- it is faster than the existing tuning methods
- it has less risks than others tuning technique
- it is non-invasive and non-destructive

The technique relies on balloons that are made of rubberized nylon that has been qualified with a pressure of 2 bar and they are designed to reproduces the cell shape in order to distribute the pressure uniformly inside the cavity and prevent (to support) the compression (the expansion) of the targeted cells. Below, Figure 4 shows the balloons set.

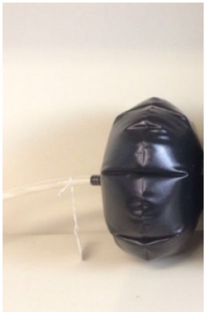


Figure 4: Rubberized nylon single cell balloon

To decide whereas a cell need to be compressed or stretched, in order to permanently change the iris-to-iris distance (i.e. changing the cavity's shape) performing a plastic deformation of the cavity and thus change both frequency of resonance and field flatness, it is necessary to measure the field amplitude trough the bead-pull measurement.

This technique lay its basis on the field perturbation with a dielectric bead and then, measuring the phase shift of the perturbed field, it is possible to retrieve the electric field amplitude in each cell. The schematic of the measure is shown in Figure 13. For more information about bead-pulling measurements see [3].

The electric field amplitude measurement show where there are peaks too high or too low that need to be smoothed or increased in order to match the frequency of resonance and field flatness requirements. So the effects on frequency and field amplitudes are the following:

- **Compression**: When a peak too high of electric field, with respect to the amplitude of the other cells is identified, the cavity need to be compressed. The effect is a decrease in both frequency of resonance and peak amplitude and the amount of frequency shift due to the compression is determined by the pressure the position of the balloons and from the amount of external force that is applied. When the target cell to compress is identified, deflated balloons are folded and inserted in all the cells apart the target one, as it can be see in Figure 6.

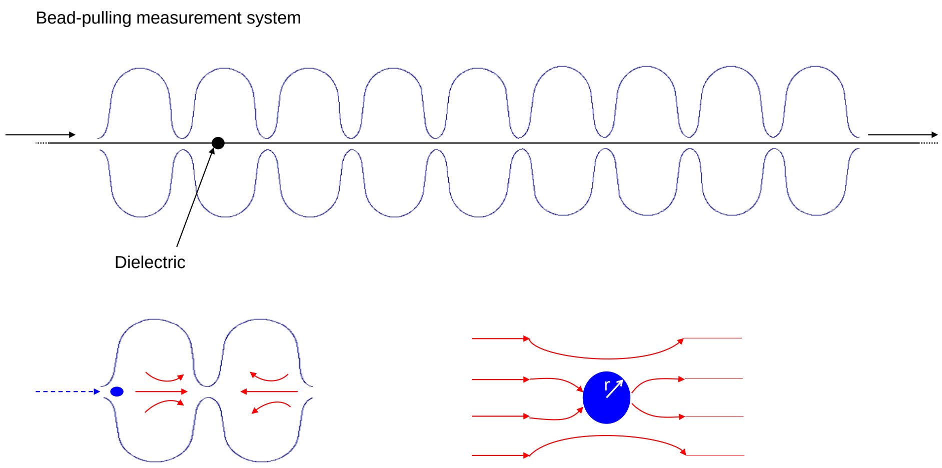


Figure 5: Bead-pull measure principle. At the top it can be seen the system set-up and at the bottom the perturbation of the field due to the insertion of the dielectric bead.

Figure 6: Deflated and folded balloons are placed inside the cells, apart the target cell, that in this case is the cell number 4.

When all the balloons are rightly placed they must be inflated and a compression force is applied, through the clamps that are placed at the cavity extremity. Figure 7 shows the cavity set up for compression.

The balloons have the duty to enhance the amount of stress that each cell need to receive in order to change shape and thus, it is easier to compress the only cell without the balloon. In other words, the balloons prevent an unwanted deformation of the non-target cells. So, in the configuration shown in Figure 7, all the cells, apart the 4^{th} undergo to a lower stress state and the target cell undergoes to an higher stress state.

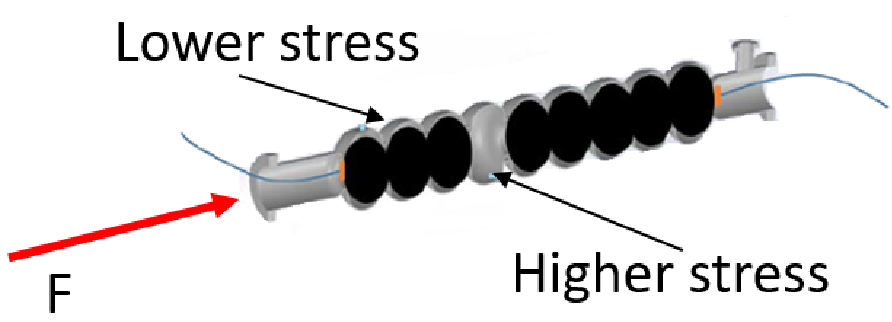


Figure 7: Above it is shown the set up for compressing the cavity and the force F is applied trough the clamps.

- **Stretching**: when a cell(s) that shows low amplitude and the resonant frequency is below the target one it is necessary to stretch the cavity. The effect of stretching the cavity is to increase the field amplitude and also the frequency of resonance. The cell shape is deformed applying both pressure and external forces and Figure 8 shows the insertion of the balloons in the target cell.

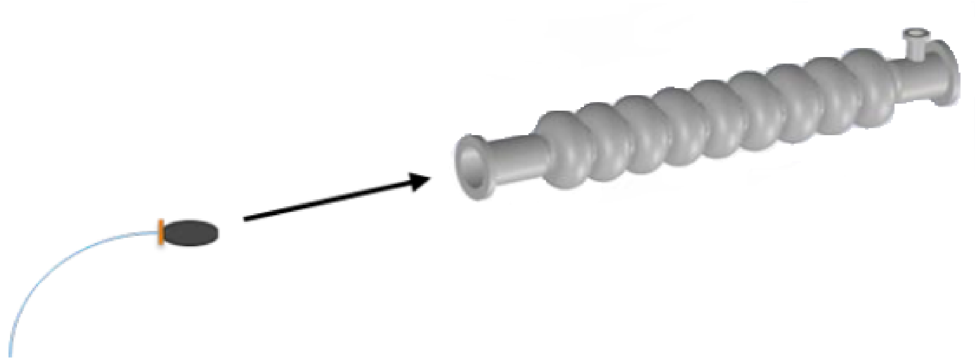


Figure 8: A single cell balloon is deflated and inserted in the target cell.

As the same as in compressing the cavity, once the balloons are rightly placed inside the cavity they must be inflated and the external force is applied trough the clamps. Figure 9 shows the cavity set up for stretching.

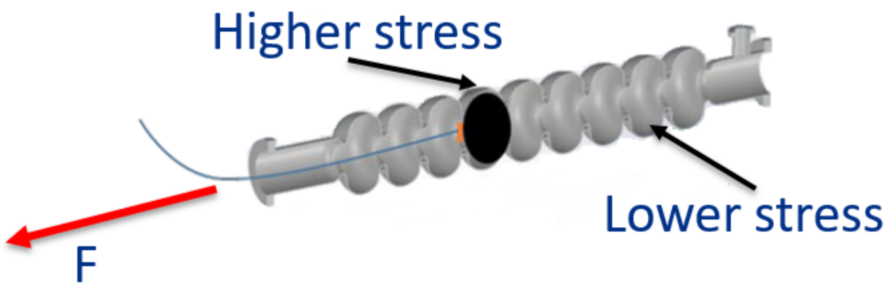


Figure 9: Above it is shown the typical set up for stretching the cavity and the force F is applied trough the clamps.

The balloon has the duty to enhance the amount of stress that is applied to the target cell in order to plastically deform the cavity.

3 Laboratory setup

In order to tune the cavity (i.e. stretching or compressing) it is necessary to set-up properly the laboratory in order to make as easier as possible all the operation on the cavity. This is necessary because if lots of tuning iterations are required, the time to tune the cavity can rapidly growth up.

Figure 12 shows the laboratory set-up needed to tune the cavity and it is composed by:

- SRF 9 cells cavity (i.e. TB9AES018, Figure 10)

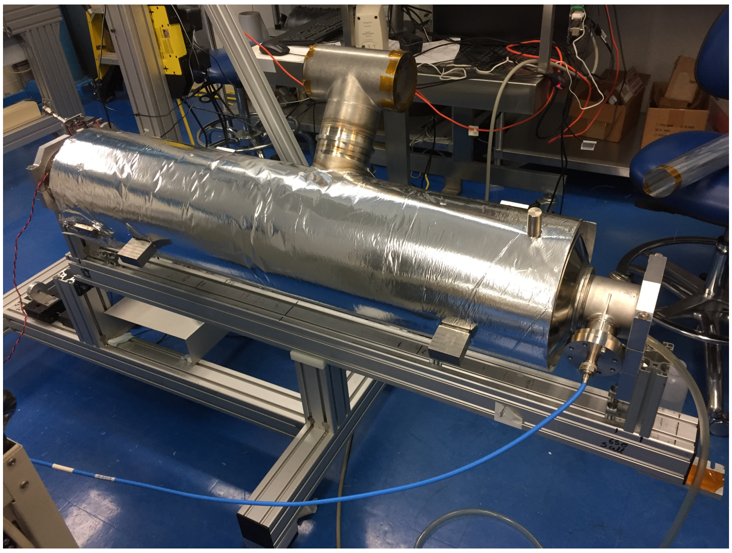


Figure 10: TB9AES018: 9 cells SRF cavity 1.3GHz for LCLS-II project

- spectrum analyzer
- power amplifier: connect the spectrum analyzer to the main coupler
- low-noise amplifier: connect the spectrum analyzer to the pick-up port
- sets of balloons (i.e. single cell, three cells, five cells ecc.)

Figure 11: Rubberized nylon balloons

- inflating and deflating system in order to pressurize balloons. This system is composed by a bottle with a manometer coupled with a regulator that has the function to regulate the pressure of the balloons. To complete the system is also necessary a relief valve in order to make the system safe and avoid overpressure.

Figure 12 shows the setup for the tuning procedure but in order to monitor the results it is also necessary to be able to easily do bead-pull measurements, as Figure 13 shows. For this reasons, it has been used a stand that gives the possibility to tilt up and down the cavity.

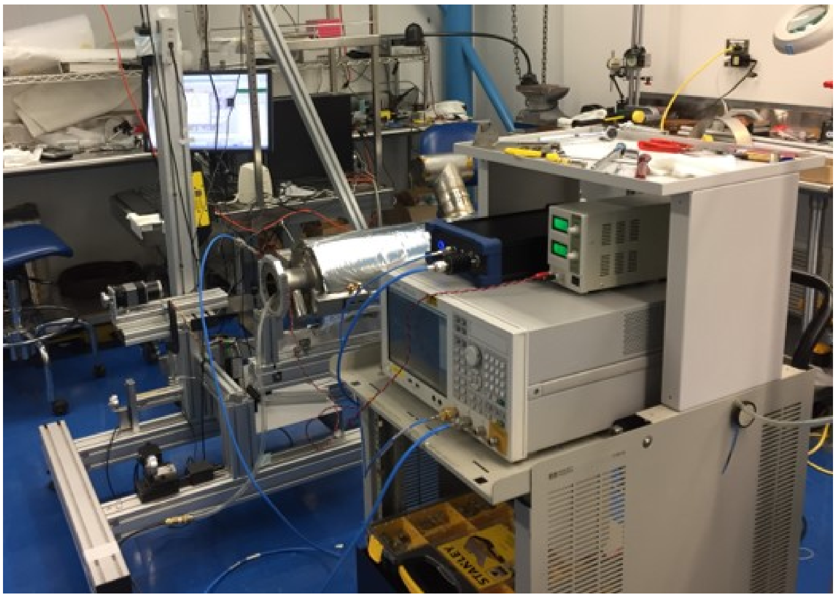


Figure 12: Laboratory set-up for Balloon Tuning Technique

The bead-pull is necessary to understand how the field amplitude and the frequency of resonance are changing and so the next tuning iterations are entirely based on these measurements.

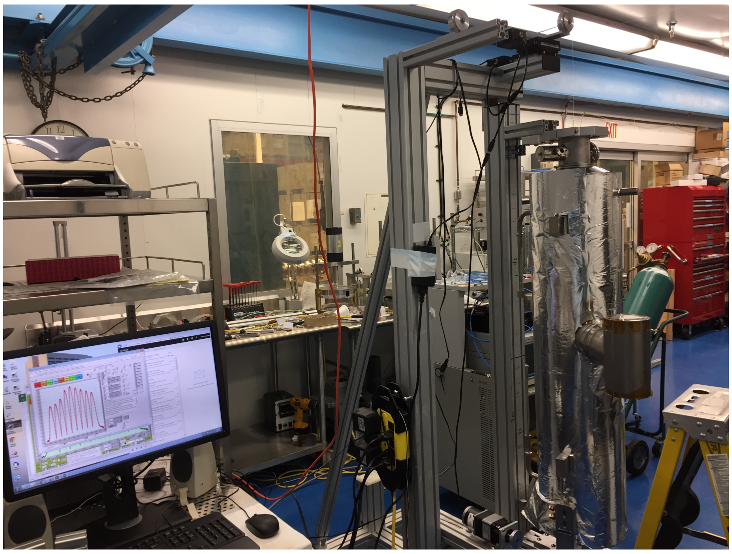


Figure 13: Bead-pull measurement system

Figure 14 shows the clamp used to apply the forces on the cavity and it is composed by an inner screw that is used to stretch and the bottom screw to compress the cavity. The displacement of the cavity under forces is not measured in term of Newton applied but rather in term of frequency shift measured during the tuning procedure.

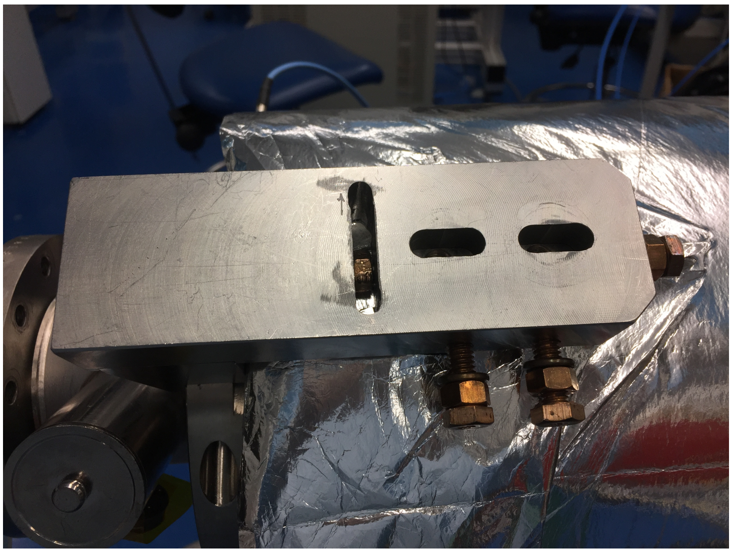


Figure 14: Clamp used to compress or stretch the cavity. The clamp act on the bottom flange of the cavity and with the inner screw it is possible to stretch the cavity. By the other side, with the screw on the right it is possible to compress the cavity.

4 Methodology

In order to tune the cavity with the Balloon Tuning Technique it is necessary to go trough several steps and iterations of compressing and stretching the cavity. The aim of this section is to give a sequence of steps, to tune the cavity, that come from practical experience. The following methodology for the balloon tuning technique is about the tuning procedure employing only one set of balloons per step. So it means that the tuning was done working on only one side of the cavity per iteration and thus lead to increase the number of steps required to reach the goal.

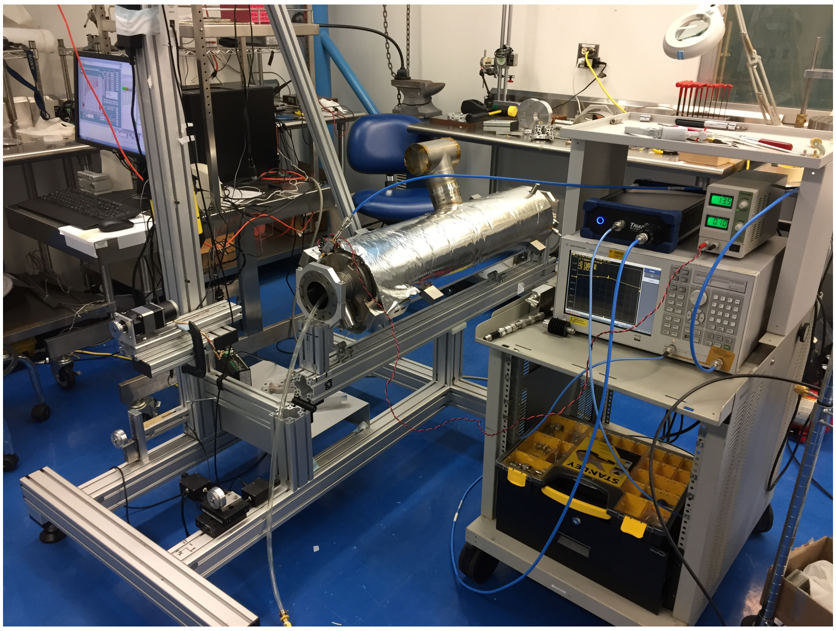


Figure 15: Balloon tuning technique laboratory setup

Step 1 Measure the frequency of resonance and field flatness through bead-pull measurement in order to determine which cell(s) has higher (lower) field amplitude and define if it is necessary to compress (stretch) the cavity.

Step 2 Before starting the tuning it is suggested to measure the centers of the cavity, so, after the several tuning iterations it is possible to know if the eccentricity specifications are met, or if the eccentricity has been affected by the tuning procedure. It is always important to keep track of the entire life of the cavity.

Step 3 After these two preparatory steps, it is time to calculate the exact amount of frequency shift that has to be reached tuning the cavity. In this project, the frequency shift is computed modelling the multi-cells cavity as coupled oscillators and solving the eigenvalues problem via Labview.

Step 4 When the exact cells (or even a single cell) that need to be tuned are identified, the balloons are deflated and folded in order to ease the insertion in the cavity. This step require to pay attention in not scratching or soiling the cavity. Once the balloons are placed inside the cavity make sure to double check if they are in the right position and if each balloon is in the right cell (Figure 16). A poorly positioned balloon(s) can deform too much the cavity ruining the tuning or, worse yet, get broken itself.

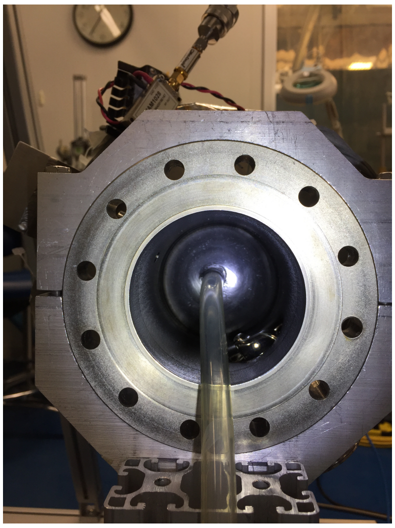


Figure 16: Correctly positioned balloon inside cell number 9.

Step 5 Once the balloons are placed, they are inflated up to 2 bar and the external force to compress or stretch the cavity is applied through special clamps designed for this purpose, as it can be seen in Figure 14. The force that is applied to the cavity is controlled from the Labview program in terms of frequency shift. During this step it is important to pay attention to the frequency shift reached under stress conditions and the residual frequency shift showed after removing the stress. It is not always straightforwardly to predict what will be the residual shift because each cell behave differently in term of hardness and softness. As an example, a cell that is going to be tuned for the first time will probably be softer than other cells that already undergoes to tuning steps. Finally, it is also important to distinguish between the residual shift in compression or in stretching and with how many balloons are placed inside the cavity (a single balloon behave differently than a set of three balloons). The residual frequency shift has to be monitored with the balloons inflated inside the cavity but without the clamps. The reason of the inflated balloons is that they change the dielectric constant of the air and thus yield to a frequency shift, but in this way the measure in more conservative.

Step 6 The next step is to remove the balloons and it can be done deflating them. This operation has to be done with care because is the main reason in damaging the balloons.

Step 7 After the tuning step a bead-pull measure is required to understand how the applied forces deformed the cavity and if the results is in accordance with the predictions. In this project the bead-pull is done putting the cavity in vertical position while the balloons are inserted when the cavity is in horizontal position.

Step 8 From the bead-pull measurement it is possible to compute which cell(s) need some other tuning steps and repeat the procedure: put the cavity in horizontal position, insert and inflate the balloons, apply the forces and see the residual frequency shift.

Step 9 Once the tuning iterations bring to satisfying results, a centers measurements is required to verify if the ellipticity meet the requirements.

Step 10 If all the three parameters (frequency of resonance, field flatness and ellipticity) are met the cavity can undergo to the cleaning procedure and to the validation test.

5 Simulations

The bare cavity has been simulated through COMSOL Multiphysics in order to better understand the cavity behaviour under stress. As software to run the simulations, COMSOL Multiphysics has been chosen because gives the possibility to couple different physics at the same time and understand how they are correlated.

The aim of this simulation is to understand the relationship between the electromagnetic fields and the solid mechanics displacement caused by the forces that are applied to the cavity during the tuning procedure. Thus, the simulation is composed by three different physics, as Figure 17 shows, or rather the electromagnetic, the solid mechanics and the moving mesh.

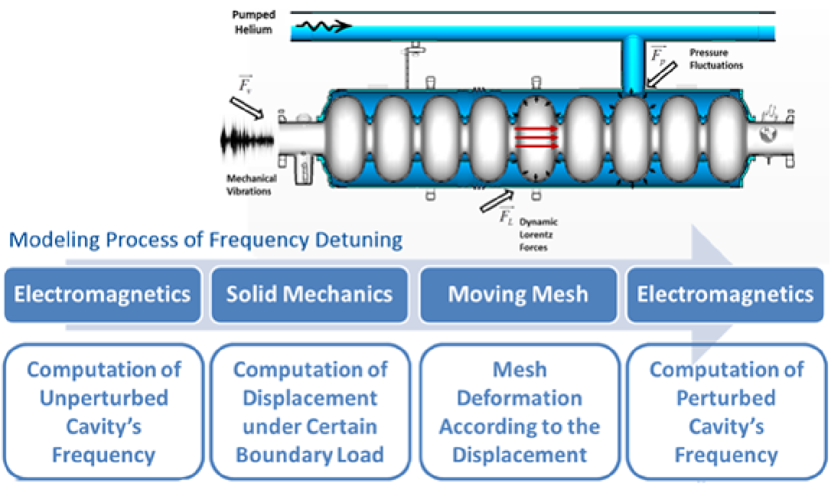


Figure 17: COMSOL Multiphysics simulation flow

The first step of the simulation is to compute the electromagnetic field that builds up inside the cavity in unperturbed conditions, or rather without any external or internal force applied. Once the electromagnetic field is computed, the solid mesh for the finite element analysis is created and applying both external forces, through the clamps, and internal pressure, though the balloons, it is possible to predict the displacement and the deformation of the cavity. Since the cavity geometry is changing it is necessary to add the moving mesh physics in order to take into account the changing in the shape. The last step, required to complete the simulation, is to compute again the electromagnetic field inside the cavity in perturbed conditions. This leads to measure the changes both in field amplitude (i.e. field flatness variations) and in frequency of resonance.

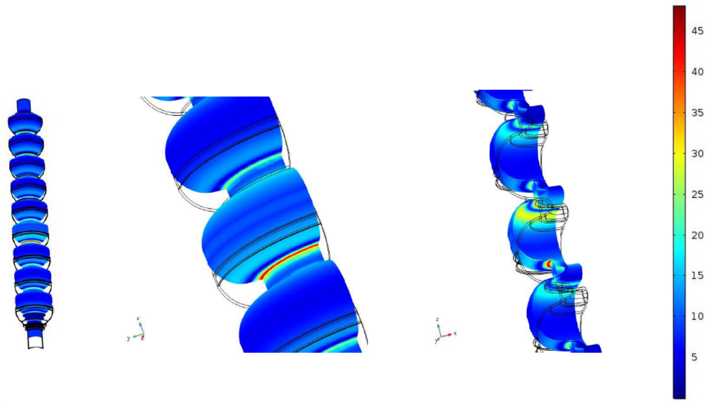


Figure 18: Compression stage of cell number 4. 3D plot of Von Mises Stress $[MPa]$ along the cavity with a balloons pressure of 2 bar and a compression force of $4kN$.

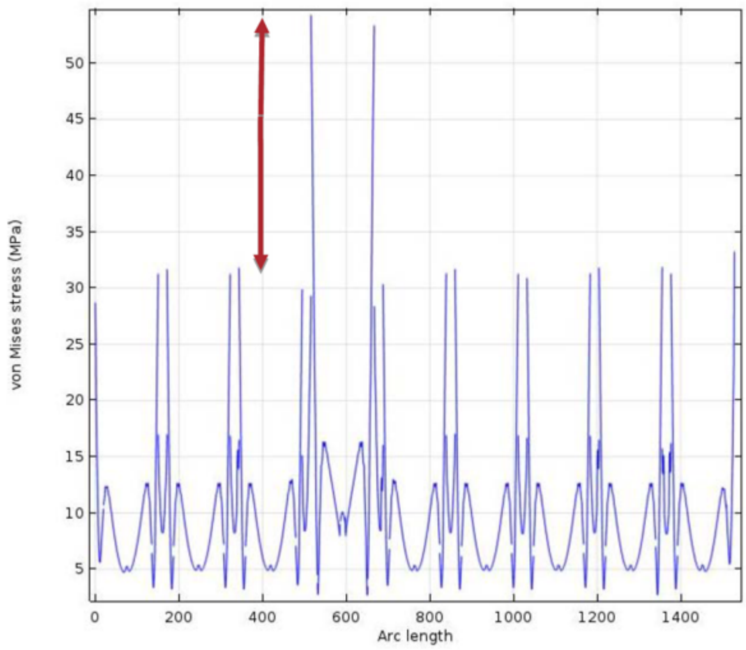


Figure 19: Von Mises Stress diagram of the compression stage of cell number 4. The stress spikes are localized on cell iris as it has been shown in Figure 18.

As example of the simulations that has been done, in Figures 18 and 19 are presented the tuning step of the fourth cell in a compression stage. In Figure 18 it is possible to see how the stress is focused on the 4^{th} cell iris, as expected and the left picture shows the geometry changes. Then, the computing of the stress on the iris cell is shown in Figure 19 that is the Von Mises Stress of the cavity computed in MPa. As it was predicted the spikes are localized on the fourth cell iris.

Similarly to what has been showed above, now it is presented a scenario where the highest amplitude of the field is detected on the end cell. This scenario is important because the ends cell often behave differently from the middle ones and stress them it is not always the best option. In the following simulation it is shown that, even if the amplitude peak is in cell number 1, it is possible to reach a good field flatness acting on the second cell. Anyway,during the experimental tuning procedure this concept has not been adopted because cell number 8 was more soft than the ends one and stretching or compressing it would have lead to an unwanted deformation. Figure 20 shows the field amplitude of the unperturbed cavity and the highest peak is localized in cell number 1 but the compression will be applied to cell number 2. This leads to compress also cell number 1 (i.e. reduce the peak) and helps in having a more uniform field amplitude, as it is shown in Figure 21.

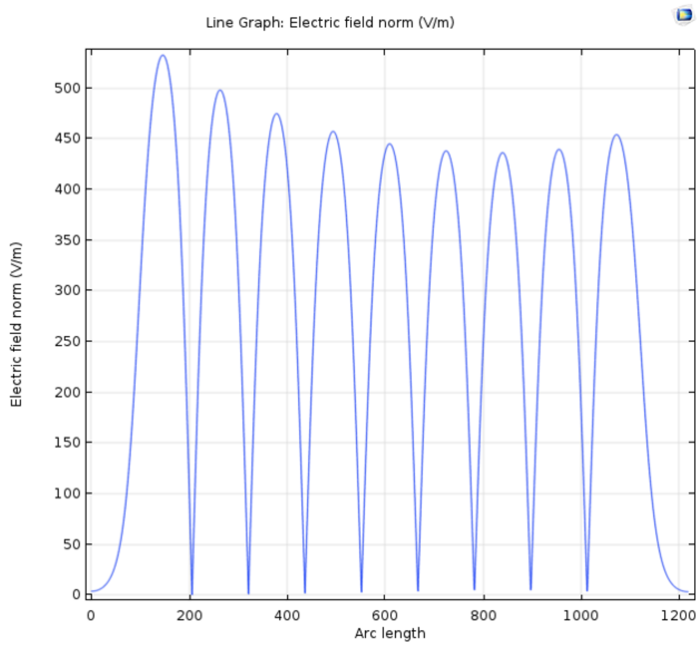


Figure 20: Field amplitude simulation of the unperturbed cavity. FF = $0,819$.

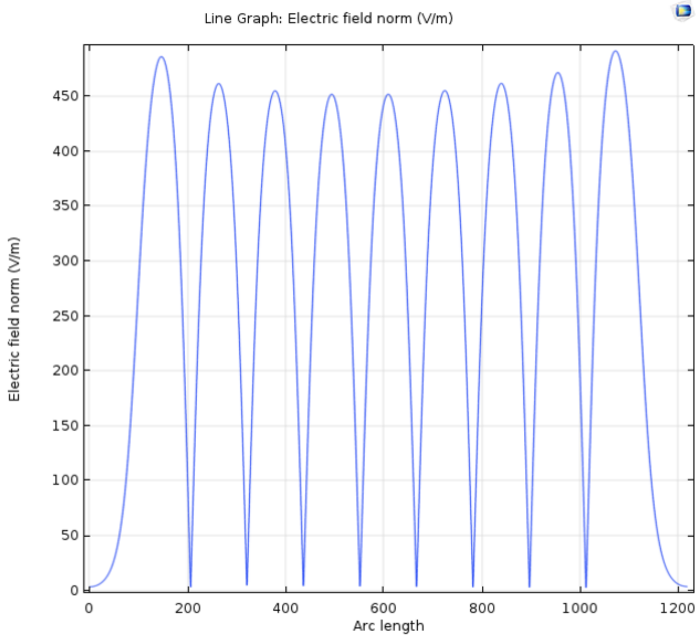
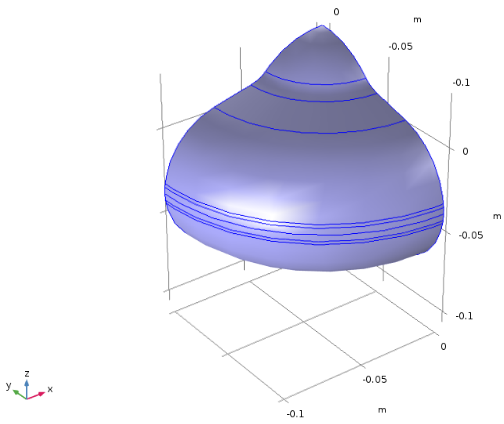
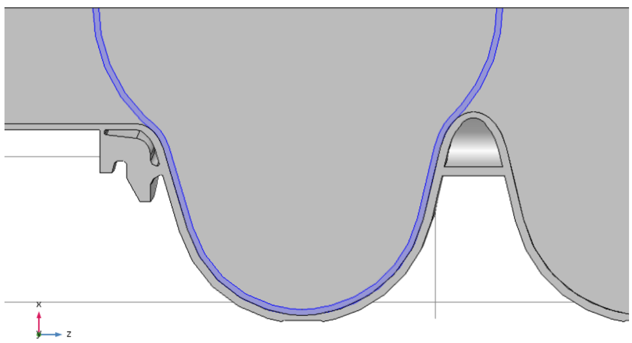


Figure 21: Filed amplitude simulation after compressing the cavity. The filed is much more uniform and the field flatness is FF = 0.919.

In order to better understand and predict how the balloon interact with the tuning procedure a COMSOL simulation has been set-up to compare measurements and simulated results. The balloon, in first instance, has been modelled as an inner shell with a thickness of $2mm$ inside the cavity, as Figure 22a shows, and thus allow to assume the hypothesis that cavity's inner surface and balloon are contacting in each point of the domain. Then, as dielectric constant has been used $\epsilon_r = 3.7$ that is the same that it is often used to modelling plastic material. In Figure 23a it is presented the balloon inside the cavity in cell number 1 and Figure 23b shows the field distribution. In the latter graph it is possible to see that the field is higher where the dielectric constant is lower, or rather, where there is not the balloon, as expected.

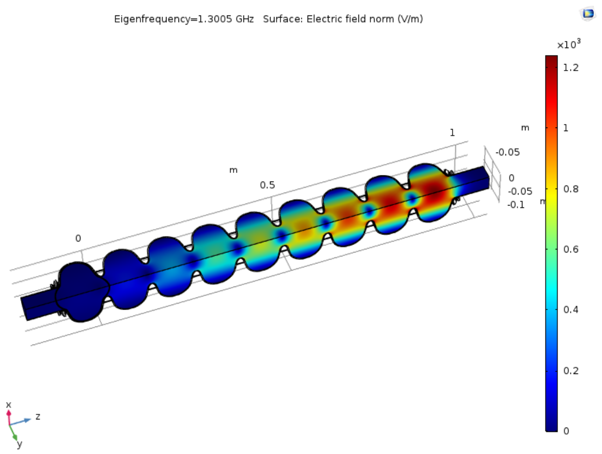


(a) Single cell balloon shape.

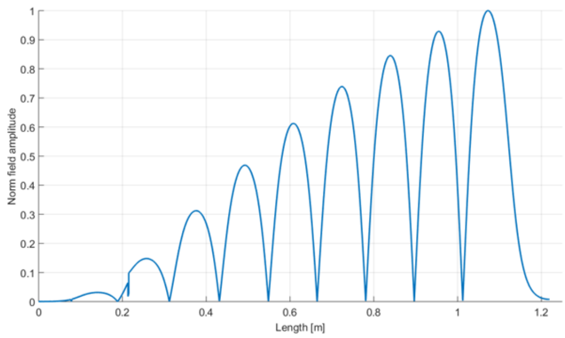


(b) Balloon placed inside cell number 1.

Figure 22: Balloon modelling in COMSOL simulation



(a) COMSOL simulation with the balloon in cell number one.



(b) Field inside the cavity when the balloon is in cell number 1.

Figure 23: Balloon modelling in COMSOL simulation

6 Results

In order to match the specifications for LCLS-II the the field flatness has to be greater than 90% and the frequency of resonance has to be comprised between $1297.91MHz$ and $1298.01MHz$. Below are presented the measurements of field amplitude and field flatness for some tuning steps. In Figure 24 it is shown the field amplitude of the cavity before starting the tuning procedure. The frequency of resonance ($f_0 = 1298.129MHz$) is slightly above the target one ($f_0 = 1297.95MHz$) and the field flatness (FF = 0.68) does not match the specification for LCLS-II. The first step is to decrease the amplitude of the cells 4 and 5, that are the highest ones, with a compression step.

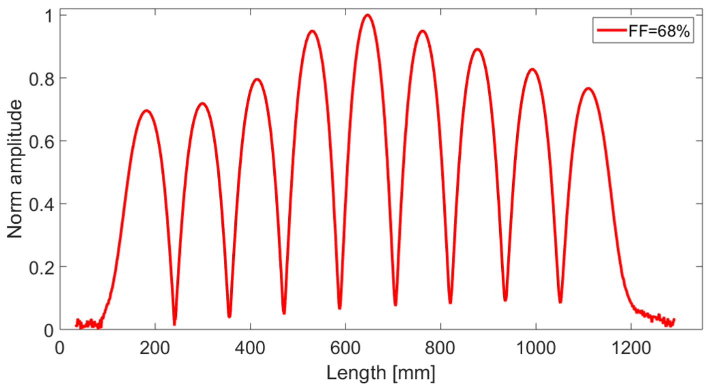


Figure 24: Bead-pull measurement of the cavity TB9AES018 before the tuninng procedure. $f_0 = 1298.129MHz$ and FF = 0.68.

During the compression of cells 4 and 5 the frequency shift under stress (i.e. inflated balloons and clamps in compression) was about $900kHz$ and the residual frequency shift was $322kHz$ (i.e. balloons inflated but without clamps). After the tuning step the frequency of resonance was $f_0 = 1297.693MHz$ and the field flatness was FF = 0.38 and they are shown in Figure 25. The field flatness, in this step, went really low but this is not an issue because the amplitudes slope is almost constant and this help in the next tuning step because stretching the cells number 7, 8 and 9 it is possible to increase again the field flatness, as Figure 26 shows. During the cavity stretching the frequency shift reached was about $309kHz$ and the residual frequency shift was of $150kHz$.

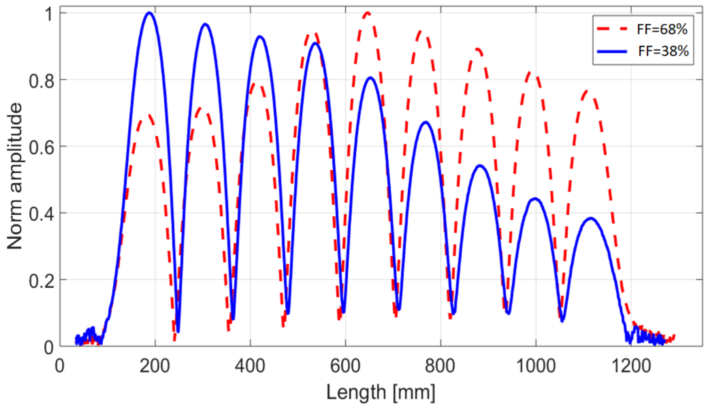


Figure 25: Bead-pull measurement of the cavity TB9AES018 after compressing cells 4 and 5. The red dashed curve is referred to the initial situation and the blue one is after compressing cells 4 and 5. $f_0 = 1297.693 MHz$ and FF $= 0.38$.

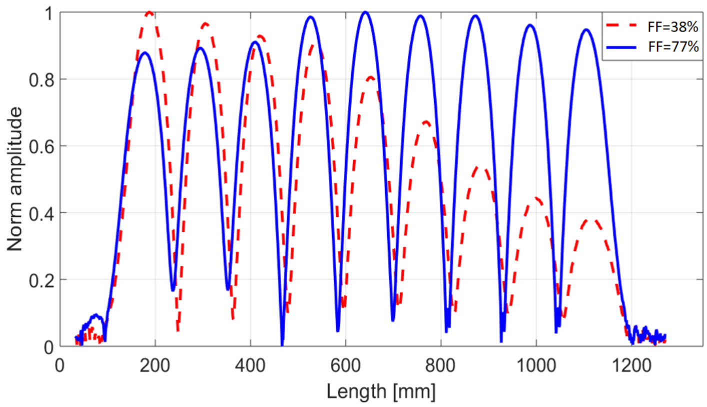


Figure 26: Bead-pull measurement of the cavity TB9AES018 after stretching cells 7, 8 and 9. The red dashed curve is referred to the previous step and the blue one is after stretching the last three cells. $f_0 = 1297.842 MHz$ and FF $= 0.77$.

The last step of the tuning procedure described here, is the stretching of cells 1, 2 and 3 in order to meet both the specifications, or rather, increase the frequency of resonance and the field amplitude of the first three cells.

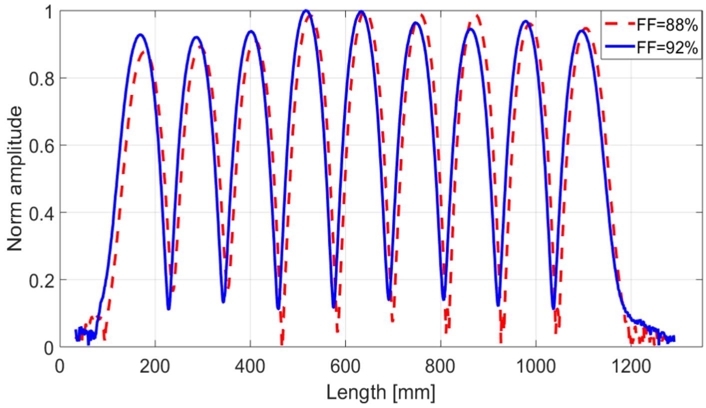


Figure 27: Bead-pull measurement of the cavity TB9AES018 after stretching cells 1, 2 and 3. The red dashed curve is referred to the previous (that is not the one showed in Figure 26 because some intermediate step has been skipped in the description) step and the blue one is after stretching the first three cells. $f_0 = 1297.924 MHz$ and FF $= 0.92$.

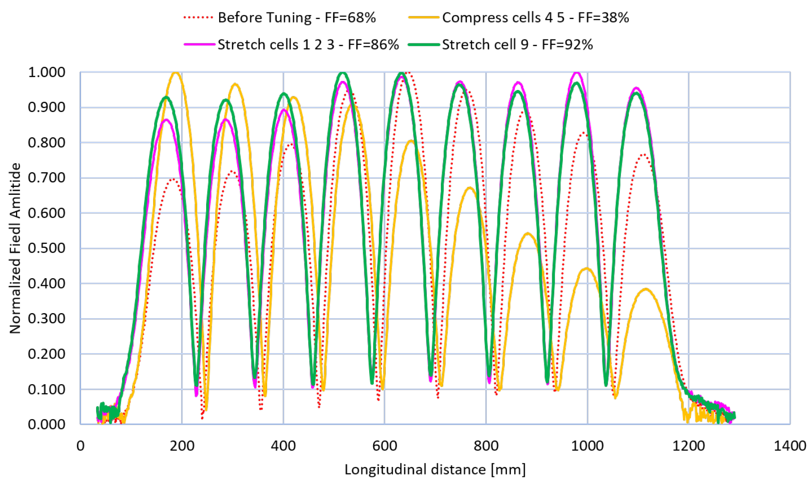


Figure 28: The steps presented before are now plotted superimposed in order to show the difference between each step.

Figure 27 and 28 shows that the requirements for LCLS-II have been met thus proving the concept of the balloon tuning technique.

In order to better understand the effects of the balloon inside the cavity, the S21 parameters and the frequency shift due to the balloon has been studied. The first measure of the S21 parameter, shown in Figure 29, is referred to a single cell balloon inside cell number one with a pressure of

15psi (red line) compared to the measure without balloon (green line). Here it is possible to see two series of resonant frequency, where the first one is due to the normal resonance of the cavity and the second one is caused by the cell number 1 with the balloon that builds-up a second series of resonance peaks.

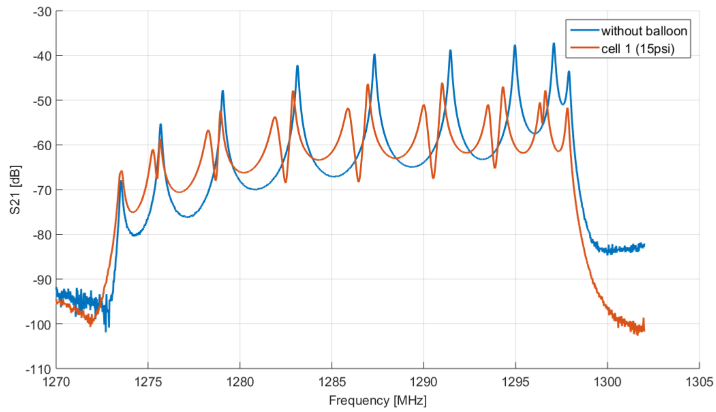


Figure 29: S21 parameter of cell number 1 with single cell balloon inflated at 15psi. The blues line is referred to the measure without balloons and the red one to the measure with balloon in cell number one.

Placing the single balloon in cell number 2 the first is not detected anymore and this is caused both from the interference of the balloon but also from the tube needed to inflate the rubber cell that pass through the first cell. This behaviour is showed in Figure 30 by the red line. The yellow line is referred to the S21 measure of the cell number 8 and it is possible to notice that the two configuration are really close due to the symmetry of the modes.

In Figure 31 is shown the effect of the balloons in cell number 3 and 5 respectively, and it is possible to notice that the distortion affect more the middle cells than the end cells, if compared with the previous graphs.

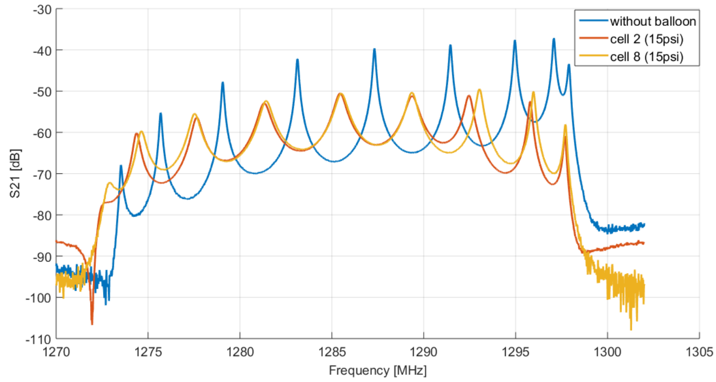
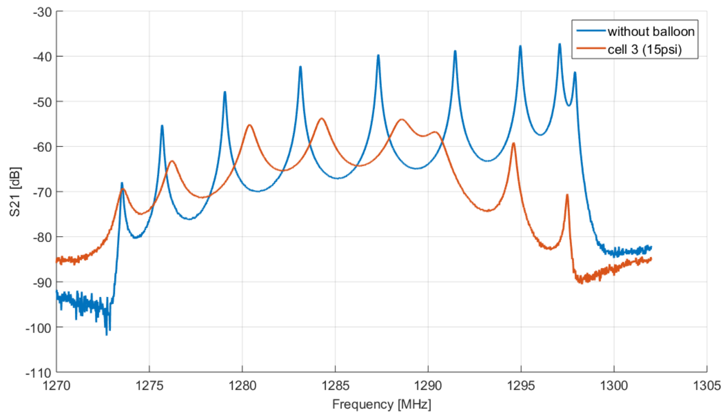
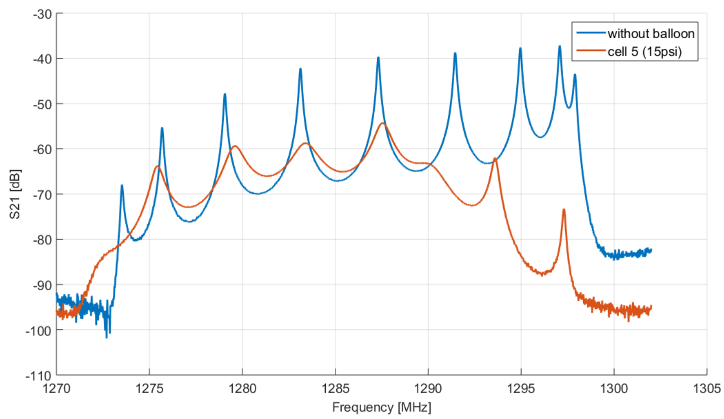


Figure 30: S21 measure without balloons is represented by the blue line, the red line and the yellow one represent the measure of cell number 2 and 8, respectively, with a balloon pressure of 15psi.



(a) S21 measure with balloon in cell number 3 (red line) with a pressure of 15psi.



(b) S21 measure with balloon in cell number 5 (red line) with a pressure of 15psi.

Figure 31: S21 measure with balloon in cell number 3 and 5, respectively. This graph shows that the middle cells suffers more the distortion due to the balloons than the end cells.

Finally, Figure 32 shows the effect of the balloon in cell number 9 and it is possible to notice that the degradation effect it is not as bigger as in the middle cells.

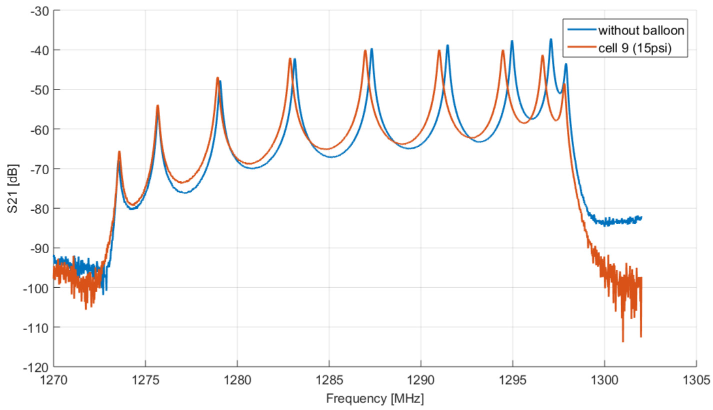


Figure 32: S21 measure with balloon in cell number 9 and a pressure of 15psi. The red line is referred to the scenario with the balloon and the green line is the measure without balloon.

Beside the S21 study, also the frequency shift induced by the tuning procedure has been analyzed and the result is that the compression or stretching of the cavity induced the desired effect on the cavity, as it is shown below.

Figure 33 is referred to a scenario where the balloons are placed in cell number 1, 2 and 3 and the goal is to compress cells 4 and 5. The balloons in the first three cells are needed to support them and prevent an unwanted deformation. The two green circles put in evidence that the compression is actually on the cells 4 and 5 and them shows a negative frequency shift as expected. It is also possible to notice that the ends cells (7 to 9) suffer an unwanted compression but this is not a big issue because stretching cell number 9, it is possible to recover the unwanted compressed cells, as Figure 34 shows. In fact, the latter graph show a positive frequency shift, prevalently in cell number 9 (where the balloon is) but in cells 7 and 8 too. This means that it is possible to recover the unwanted compression of the earlier pushing stage without affecting cells 4 and 5, or rather the target cells of the compression stage.

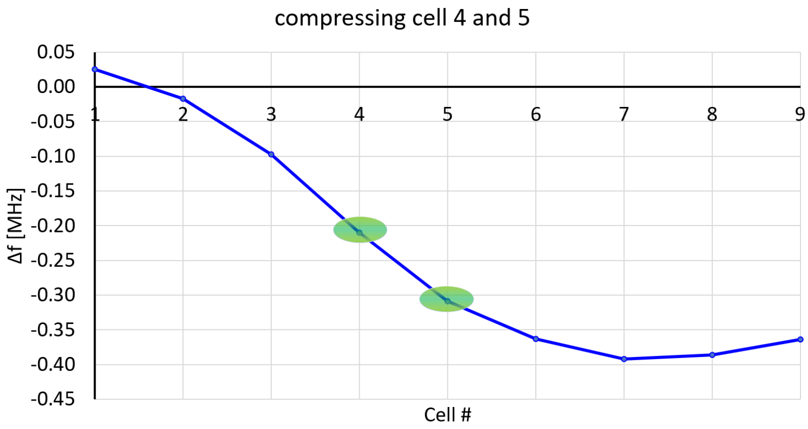


Figure 33: Compressing stage, during the cavity tuning, with balloons in cells 1,2 and 3 with the aim to compress cell 4 and 5 that shows high peaks of field amplitude. The green circles evidences the target cells.

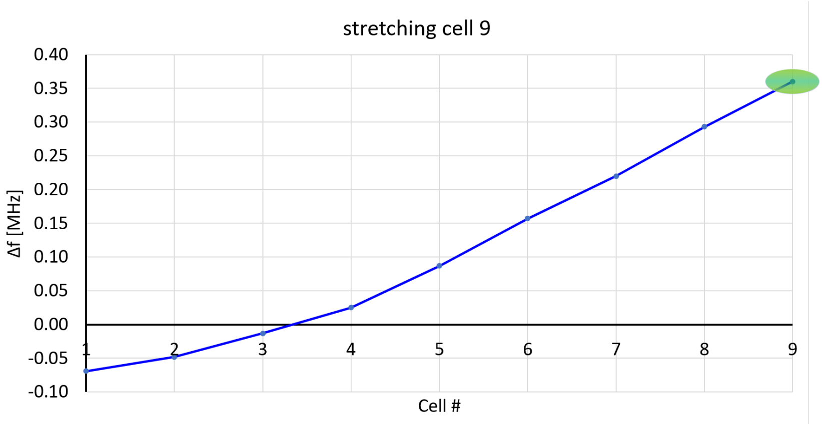


Figure 34: Stretching stage of cell 9 with single balloon. This graph shows that the frequency shift in cell number 9 is positive, as expected from a stretching stage, and also taht it is possible to recover the undesired effect of a previous compression stage on cells 7 and 8.

In Figure 35, instead, it is shown the effect of the stretching stage employing a three balloon set placed in the first three cells of the cavity. Also in this scenario the effect of the balloons in the one desired.

Figure 35: Stretching stage of cells 1, 2 and 3 with a three balloons set. The graph show a positive frequency shift on cell 1, 2 and 3 as expected.

During the stages of tuning, even if the graphs presented shows that the frequency shift caused by the balloon is almost predictable, there are some cases where it is not straightforwardly to pre-calculate how much the shift will be. As example of this, Figure 36 shows that during the stretching of cell number 8, the residual frequency shift is far bigger than expected. This is due to the softness of the cell number 8 that has never experienced a tuning step with a single cell balloon. It is now that the effect of a single cell balloon or a set of more balloons is different on the cavity because of the redistribution of the forces.

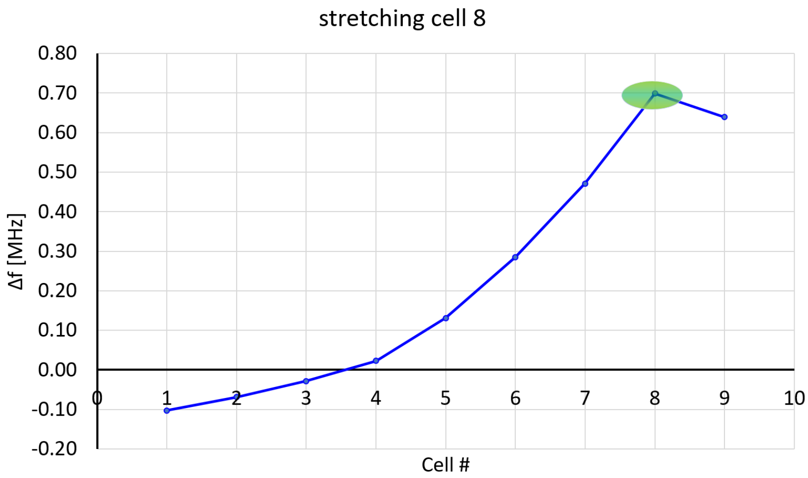
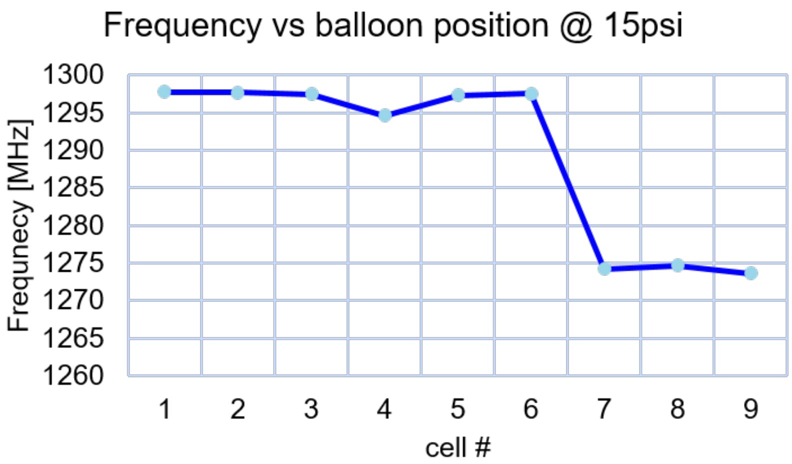
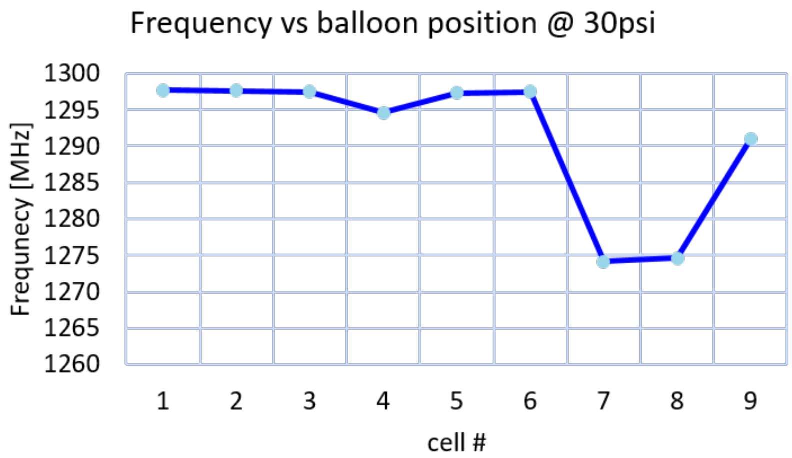


Figure 36: Stretching stage of cell 8. Here it is possible to see that, even if the shift is positive as expected, the amount of the shift it is not the predicted one.

The last studies that are presented about the sensitivity of the cavity related to the balloons, are the dependence of the frequency versus balloon position and pressure. In Figure 37 is shown how the frequency is affected from the balloon position. The measure is a series of measure where the single cell balloon has been moved to each cell in order to measure the pi-mode frequency. The results, in both scenario (15psi and 30psi) is that the ends cells suffers more the presence of the balloon if compared to the firsts cells. It is also possible to investigate the frequency shift versus the balloon pressure, as it can be seen in Figure 38, and the lower the pressure the higher the impact on the frequency. The same study can be done for all the others cells with similar results.



(a) Frequency shift due to the presence of the single cell balloon with a pressure of 15psi.



(b) Frequency shift due to the presence of the single cell balloon with a pressure of 30psi.

Figure 37

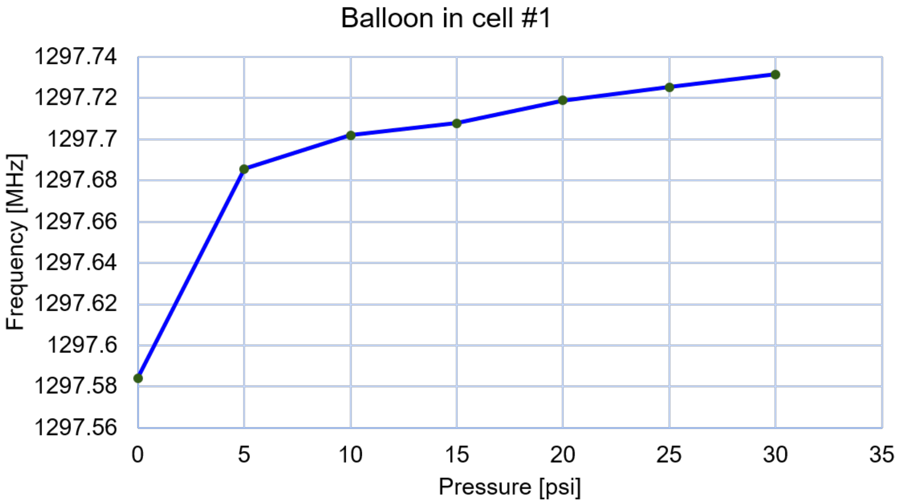


Figure 38: Frequency shift versus the balloon pressure in cell number 1.

7 Conclusions

Nowadays, the tuning of jacketed cavities is an open problem and the already developed techniques shown that there are lots of issue to deal with. The main problems of the existing techniques are that, when a cavity is detuned, it is necessary to remove the vessel and adjust the resonant frequency and (or) the field flatness; then weld a new helium tank outside the cavity. This procedure, as it can be easily noticed, is both expensive and full of risks. So, the importance to develop new non-invasive tuning techniques is mandatory to solve detuning problems, that can occur for different unexpected causes (i.e. improper handling, improper cavity supporting, cavity overloading, etc.) and can affect big experiments as like as XFEL and LCLS-II experienced.

These problems pave the way for a new generation of tuning systems that are based on the idea to not remove the vessel. This is exactly the aim of the Balloon Tuning Technique and the idea behind this novel procedure is to access the cells form inside and so it is not necessary to go through the several and risky steps of removing the vessel, tune the cavity and weld a new one. The the Balloon Tuning Technique lay its foundation on the idea to put pressurized balloons inside the cavity and mechanically applying compression/traction forces at the flanges in order to produce a plastic deformation of the cavity and thus adjusting the resonant frequency and the field flatness.

In this project, it has been shown the validity of the concept, both theoretically and experimentally, and the results show that it is possible to meet the LCLS-II specifications in a reduced number of steps and relatively short time. Furthermore, the cost of this technique is really low if compared with the already existing tuning techniques. During this project I have advanced the starting point for further development for a new generation of tuning techniques, indeed, and it can change the entire know how of manufacturing and qualifying multi-cell cavities at FermiLab.

References

[1] U.S. Department of Energy, "The benefits of particle accelerators for society."

[2] T. H. Hasan Padamsee, Jens Knobloch, *RF superconductivity for accelerators.*

[3] H. Wang and J. Guo, "Bead-pulling measurement principle and technique used for the srf cavities at JLab."