



SAPIENZA
UNIVERSITÀ DI ROMA

Impedance study on HL-LHC's collimation and protection system

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Dedicato al mio caro nonno, che ci guarda dall'alto

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Chapter 1

Introduction

1.1 Objectives

In this thesis work the coupling impedance of the foreseen HL-LHC's (High Luminosity Large Hadron Collider) collimation and protection system will be analyzed in detail. In particular the devices of interest will be the TCSPM and the TDIS, which are a secondary collimator and an injection protection system. This work is structured in two parts, the first one is composed by three chapters in which it will be explained: what are the LHC and the collimators, which formulas were used in order to carry out this study, which tools and measurements techniques were adopted to characterize the different materials. The second part is composed of two chapters and it will show and comment the results obtained during a year of studies.

1.2 The LHC and his collimation and protection system

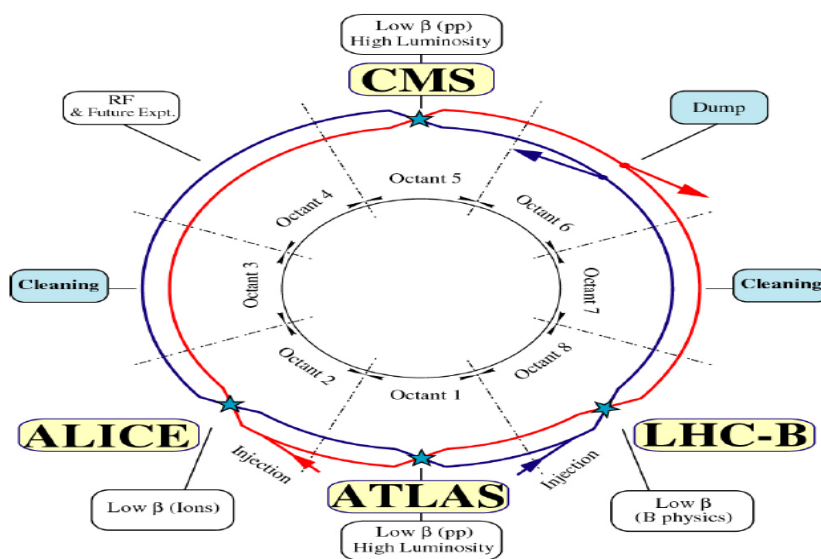


Figure 1.1. LHC Ring

The Large Hadron Collider is a state-of-art protons and ions accelerator built in order to achieve the highest possible energy and luminosity values. It is long 27 km and it has been built in a tunnel 100 meters under the ground. This machine is able to confer to a single bunch the record energy of 7 TeV, leading to head-on collision energy of 14 TeV. The LHC is made of eight arcs and eight insertions. An insertion consists of a long straight section and it has one specific purpose, which could be particle colliding, particle injection, beam cleaning, beam dumping and so on. Each one of these functions have a basilar role in the life of LHC, the ones in which the thesis work is mainly focused are the dumping section and the cleaning or collimation one. In picture 1.1 all the different octants of LHC are shown, with all the different functions and collision points represented. The upgrade of this machine foreseen for the next year is the High Luminosity LHC, which has the target to increase the luminosity achieved so far by LHC by changing his optics, increasing the number of particles per bunch and by reducing his coupling impedance.

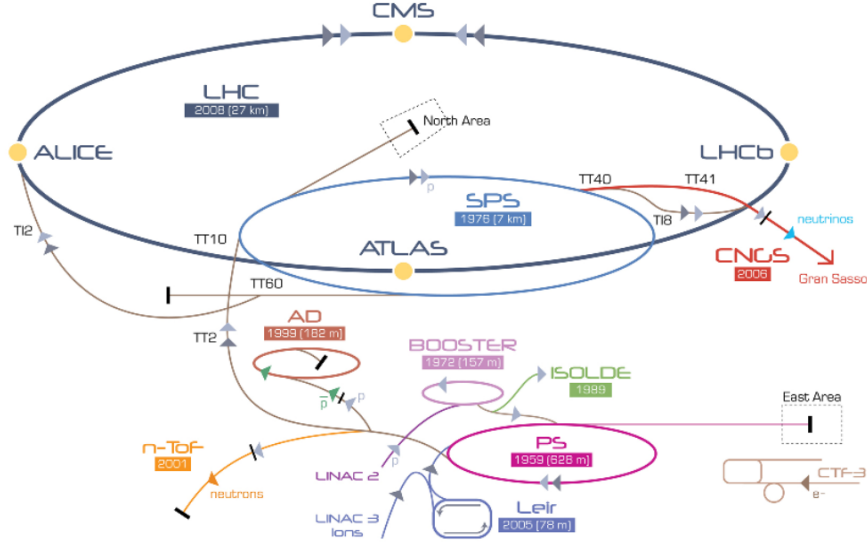


Figure 1.2. CERN full ring's chain

The LHC is part of a big complex chain of many components, as shown in picture 1.2. Many smaller accelerators contribute to the chain as the Super Proton Synchrotron (SPS), the Proton Synchrotron (PS), The LEIR (Low Energy Ion Ring) and all the different Linear accelerators for injection (Linac2, Linac3 and in the coming future Linac 4). The four main collision points of all the complex are reported with yellow dots in the image and they represent the position of the experiments: ALICE, CMS, LHCb, ATLAS.

The cleaning system in LHC is a really important section of the accelerator because it is able to act directly on the beam via its collimators

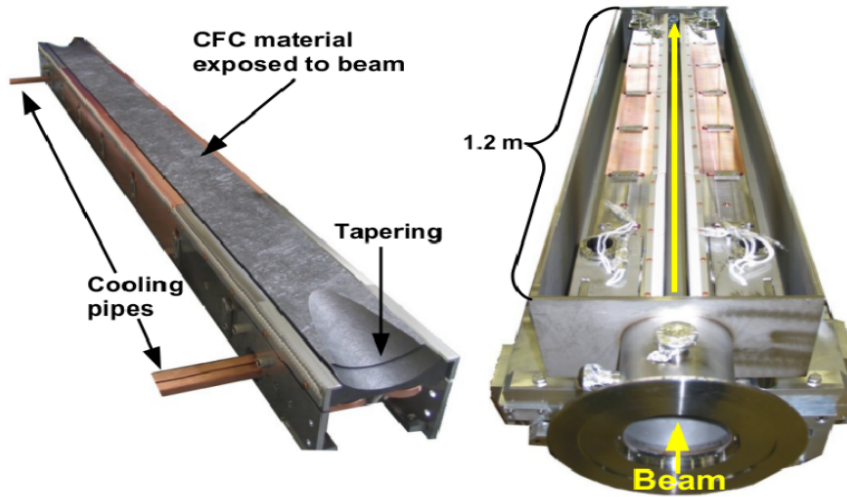


Figure 1.3. Collimator's jaw and collimator top view

A collimator is a device situated in a straight section which is able to remove the exceeding particles from the different bunches composing the beam: in order to achieve this it has been equipped with two long blocks of absorbing material (jaws) which are able to move up and down in order to control the aperture with respect to the beam itself. The role of the collimation system are (Ref.[13]):

- Cleaning of the halo (the portion around the bunch which is not useful for collisions),
- Reduction of total doses to accelerator equipment to provide local protection to particularly sensitive devices,
- First line of defense in case of significant machine failures,
- Reducing the impact of scattering particles on experiment's data, which can produce a significant amount of noise while acquiring from collisions,
- Concentration of losses and radiations in specified areas in order to simplify the maintenance of the accelerator,

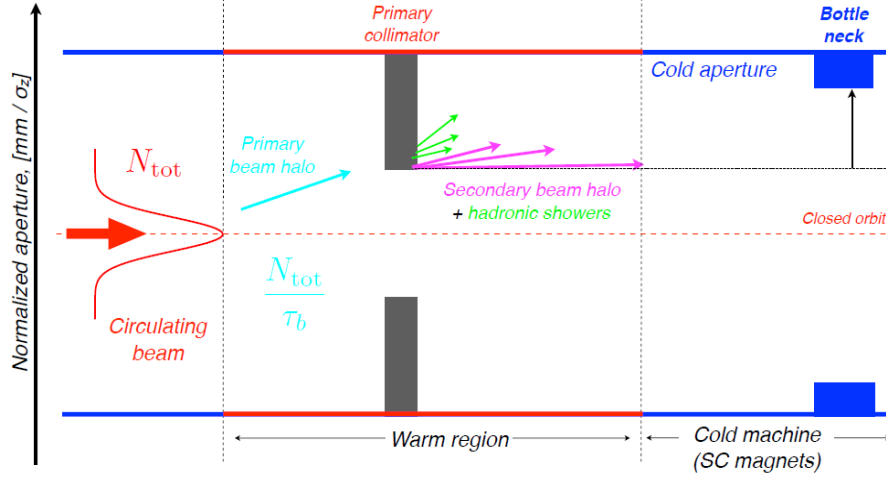


Figure 1.4. One stage collimation system

The idea of collimation is shown in picture 1.4 where a beam composed by a single bunch is circulating along the machine. Assuming a Gaussian distribution the bunch will act as shown, propagating particles in the transversal direction: the particles lost from the beam core literally drift transversally and create what are called "beam tails". These tails represent the part of the bunch which is able to move away from the core and hit the machine, as mentioned before, causing many issues and bad beam parameter's relevations. As visible in the picture many particles from the halo are still in the condition to hit the machine, in order to avoid this the collimation used in LHC has been built in a different way:

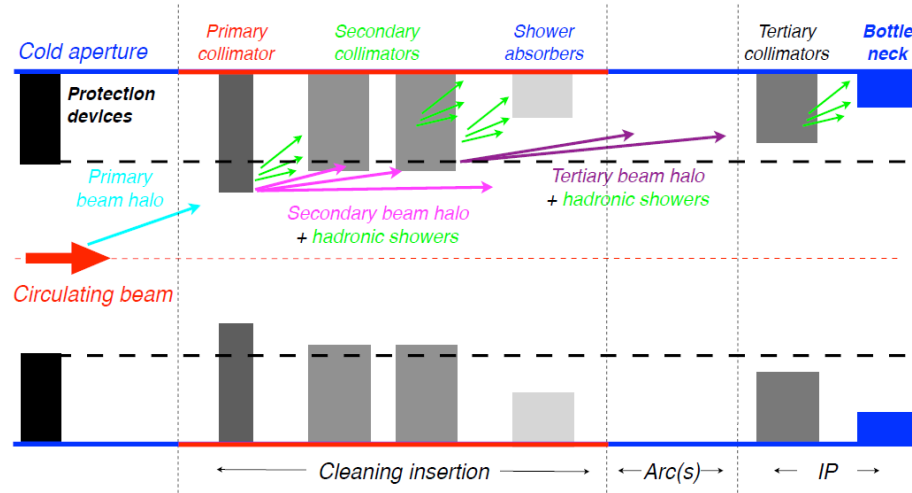


Figure 1.5. five stages collimation system

The collimation structure is composed by a 5-stage cleaning system. The first

element to be removed from the beam itself is the primary halo, on which are directly acting the primary collimators. The secondary beam halo has been taken care of by secondary collimators and the tertiary halo by the tertiary collimators. In this way the final beam halo coming out from the collimation system has been significantly reduced respect to the previous configuration: the scattering particles have been controlled with a better accuracy and a better LHC performance can be achieved.

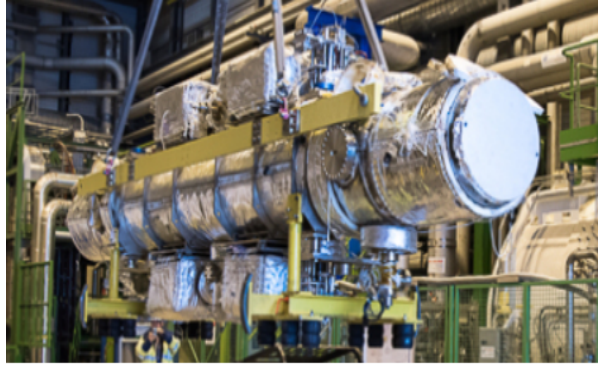


Figure 1.6. TDI during transportation

The protection system is conceived in a similar way to a collimator but with a different purpose and position in LHC ring. It is larger than a normal collimator and it is divided in three tanks: each one is containing two jaws made of graphite in order to absorb the energy coming from the beam. In fact the function of the protection system is to protect the accelerator's cold mass in the scenario in which the injection kicker isn't working properly: as show in the next picture the beam after passing the septum needs to be kicked to enter inside the machine along his design orbit, if this doesn't happen the graphite jaw will absorb all the energy coming from the accelerated particles.

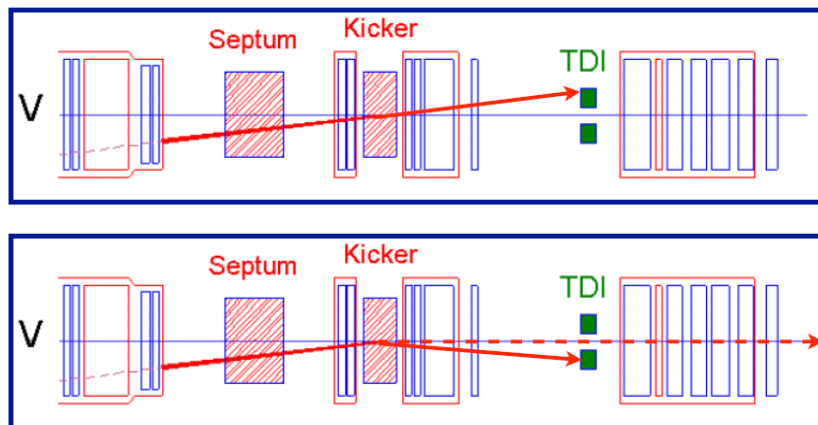


Figure 1.7. TDI's protection role

The second scenario in which the TDI absorber proves useful is when an asynchronous kicker firing condition is verified: this will imply again a significant beam deviation from his reference orbit, leading the particles to impact a component in the tank. Both these conditions are dangerous for the safety of LHC, these failures could lead to serious machine damage and related effects involving all the ring.

Chapter 2

Notions of Beam Physics and Beam Coupling Impedance

2.1 Main Equations and Parameters of a Particle Collider

2.1.1 Luminosity

In a particle collider many parameters and equations are used to comprehend the machine itself and the behaviour of the particles passing through it. One of the main parameters used to understand the quality of the results obtained by a collider is the luminosity, which expresses the number of interactions in proximity of a collision point (Ref.[4])

$$L = f \frac{N(n_1 n_2)}{4\pi\sigma_x\sigma_y} \quad (2.1)$$

In this equation N bunches containing n_1 and n_2 particles are colliding with frequency f . σ_x and σ_y characterize the Gaussian transverse beam profiles in the horizontal and vertical directions. In order to simplify the expression it is assumed that the bunches are identical in the transverse profile, that the profiles are independent on the position along the bunch, and the particle distributions are not altered during collision. If now the transverse beam sizes are considered and the β function is introduced the luminosity can be expressed also in an equivalent form

$$L = f \frac{N(n_1 n_2)}{4\sqrt{\epsilon_x \epsilon_y \beta_x \beta_y}} \quad (2.2)$$

The β_x and the β_y in the equation are the values in proximity of the collision point, where the optics is forcing the two functions to be as small as possible, to achieve the best possible collision rate in the machine. The event rate is directly proportional to the luminosity L and it can be written as

$$L = R\sigma_{int} \quad (2.3)$$

where σ_{int} represents the interaction cross section, derived via statistical approach.

2.1.2 Tune and Betatron Oscillations

Present day high energy accelerators employ alternating gradient focussing provided by quadrupole magnetic fields. The equations of motion of a particle undergoing oscillations with respect to the design trajectory are

$$\ddot{x} + K_x(s)x = 0, \quad (2.4)$$

$$\ddot{y} + K_y(s)y = 0, \quad (2.5)$$

$$K_x = \frac{\dot{B}}{B\rho} + \rho^{-2}, \quad (2.6)$$

$$K_y = -\frac{\dot{B}}{B\rho}, \quad (2.7)$$

where $\dot{B} = \frac{\partial B_y}{\partial x}$, ρ is the bending radius and all the derivatives are respect to the position s along the trajectory.

This motion along the ring is called betatron oscillation because it was initially studied in the context of that type of accelerator (Ref.[13]). The functions K_x and K_y represent the transverse focussing force due to quadrupole fields (except for the term ρ) so each equation of motion resembles an harmonic oscillator but with spring constants that are a function of position. The solution for one of the plane is then

$$x(s) = A\sqrt{\beta_x(s)}\cos(\psi_x(s) + \delta) \quad (2.8)$$

where $\frac{d\phi}{ds} = \frac{1}{\beta}$ stands for the phase advance in the machine, which depends on the betatron function defined by the design optic. The term A is an integration constant and its dimension is the square root of length. The amplitude of the oscillations it is dependent on the square root of the β function. The wavelength of a betatron oscillation may be some tens of meters, depending on the position inside the accelerator itself. The beam optics arrangement generally has some periodicity and the amplitude function is chosen to reflect that periodicity, in order to achieve the specified beam size along the design orbit. As mentioned before, a really small value of the amplitude function is desired at the interaction point. The number of the betatron oscillations per turn is called the tune and it is represented by

$$Q_{x,y} = \frac{1}{2\pi} \int \frac{ds}{\beta_{x,y}} \quad (2.9)$$

This is a fundamental parameter in a modern accelerator, it depends on the magnet optics all along the machine and it is set up to precise values in order to avoid instabilities, resonances and other dangerous phenomena.

2.2 Wake Fields and Coupling Impedance

The collective effects are responsible for many phenomena which limit the performance of an accelerator in terms of beam quality (Ref.[6]). These effects are the ones related with the coherent motion of a significant number of particles, and they appear when protons in a bunch feel the perturbing electromagnetic field due to the interaction of the beam with its environment. The beam travelling inside a vacuum chamber induces electromagnetic fields which may affect the dynamics of the beam itself: this interaction is what is called impedance, and it is one of the main contributor to beam intensity limitations due to coherent effects (together with electron cloud, beam-beam related effects and others).

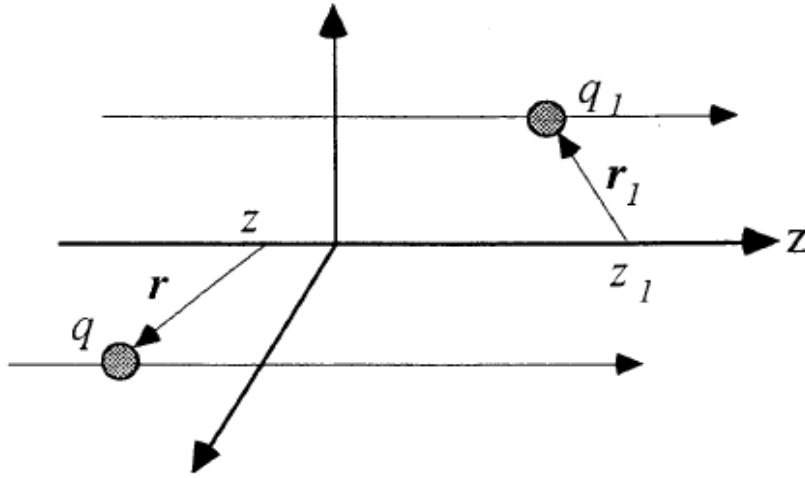


Figure 2.1. Two charges moving in a reference system

2.2.1 Longitudinal Wake Field and Longitudinal Impedance

An accelerator can be seen as a feedback device, where any longitudinal or transverse perturbation appearing in the beam distribution may be amplified or damped by the electromagnetic forces generated by the perturbation itself. The electromagnetic fields induced by the beam are called wake fields due to the fact that they are left behind the travelling charge, considering that β (speed of the particle over speed of the light) is considerably close to 1. Now the reference system of picture 2.1

is assumed where two point charges q and q_1 are travelling with velocity βc on trajectories parallel to the axis inside a vacuum chamber. If we define as r_1 the transverse distance of the charge q_1 from the z axis and r the transverse distance of the charge q from the z axis, the electromagnetic force acting on q and produced by q_1 will be

$$F(r, z, r_1, z_1; t) = q[E(r, z, r_1, z_1; t)] + vB(r, z, r_1, z_1; t)) \quad (2.10)$$

This Lorentz force generated can affect the dynamics of the charge itself and on any trailing charge as well in the scenario where β is smaller than one. If now the time delay τ of the trailing charge with respect to the leading one is defined, the coordinates of the two are defined as $z = vt$ and $z_1 = v(t - \tau)$.

The energy lost by the charge q_1 due to the longitudinal force given by the charge q is computed as the work done by the longitudinal electromagnetic force along the structure

$$U_{11}(r_1) = - \int_{-\infty}^{\infty} F(r, z, r_1, z_1; t) dz, \quad (2.11)$$

with $t = z_1/v$

The energy lost by the trailing charge under the effect of the electromagnetic field produced by the leading one is then

$$U_{21}(r_1) = - \int_{-\infty}^{\infty} F(r, z, r_1, z_1; t) dz, \quad (2.12)$$

with $t = z_1/v + \tau$

Considering that the particles are moving on trajectories parallel to the z -axis the only field component giving a contribution to Lorentz Force is the longitudinal component of the electric field E_z . The integration has been considered as performed over an infinite structure: this is not always possible, if the case considered is a vacuum chamber then the evaluation can be extended to infinite. In other scenarios such as bellows or additional transverse cavity this procedure can give a good estimation of the energy lost as long as the wavelength of the field is significantly shorter than the length of the device itself. It is also important to keep in mind that these equations are working in the scenario where the speed of the particles and the shape of the bunch aren't affected by the wake fields, otherwise equations 2.11 2.22 are not applicable anymore.

The loss factor k is defined as the energy lost by q_1 per unit charge squared

$$k(r_1) = U_{11}(r_1)/(q_1)^2 \quad (2.13)$$

and it represents the energy lost by the leading particle. The longitudinal wake factor is defined as:

$$w_z(r, r_1; \tau) = U_{21}(r, r_1; \tau)/(q_1 q) \quad (2.14)$$

Both the loss factor and the wake function are expressed in V/C . From the wake function previously defined it is possible to compute the wake potential produced by any bunch distribution. If now a bunch of particles is considered as the leading charge, travelling at a distance r_1 from the z axis and with a longitudinal distribution

$$q_1 = \int_{-\infty}^{\infty} i_b(\tau) d\tau \quad (2.15)$$

the wake potential produced by this distribution at a point with time delay τ can be computed by performing the convolution between the wake function over the bunch distribution itself. The convolution integral will be performed by applying the superposition principle: the distribution will be split into an infinite number of slices and the contribution of each of the slice to the wake will be summed up. The energy lost by a trailing charge q because of the wake produced by the slice at τ' is

$$dU(r, \tau - \tau') = q i_b(\tau') w_z(r, \tau - \tau') d\tau' \quad (2.16)$$

And if all the effects are summed together

$$W_z(r, \tau) = \frac{1}{q_1} \int_{-\infty}^{\infty} i_b(\tau') w_z(r, \tau - \tau') d\tau' \quad (2.17)$$

The last equation represents the wake potential, which is basically the full structure response in terms of electromagnetic force to a stimulus provided by a bunch of particles. This object is something really useful in the accelerator physics field, it can fully describe a device in terms of electromagnetic interaction with a bunch. By applying again the superposition principle also the wake loss factor can be computed for a bunch distribution

$$K(r) = \frac{1}{q_1} \int_{-\infty}^{\infty} W_z(r, \tau) i_b(\tau) d\tau \quad (2.18)$$

From these definitions now the wake impedance can be defined, by performing a Fourier transformation on the wake function

$$Z(r, r_1, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} w_z(r, r_1, \tau) \exp^{-j\omega\tau} d\tau \quad (2.19)$$

This object is called coupling impedance and it is measured in Ohm and it is a complex quantity

$$Z(r, r_1, w) = Z_r(r, r_1, w) + jZ_i(r, r_1, w) \quad (2.20)$$

where the Z_r is an even function and Z_i part is an odd function. This can be proved considering that the wake function is a real function of τ via expanding the integral in the Fourier transform of the wake function and proceeding via mathematical passages.

The wake function can be then derived back from the longitudinal impedance by applying the following inversion of Fourier transform

$$w_z(r, r_1, \tau) = \int_{-\infty}^{\infty} Z(r, r_1, \omega) \exp^{j\omega\tau} d\omega \quad (2.21)$$

The same equations can be applied also in the transverse plane.

2.2.2 Transverse Wake Field and Transverse Impedance

If now the the leading charge is transversally displaced with respect to the path of the trailing charge the effect produced is quite different. This displacement is now producing inside the given structure field components responsible for transverse effects. The force experienced by the trailing particle is expressed as a transverse momentum kick

$$M_{21}(r, r_1, \tau) = - \int_{-\infty}^{\infty} F_{trans}(r, z, r_1, z_1; t) dz \quad (2.22)$$

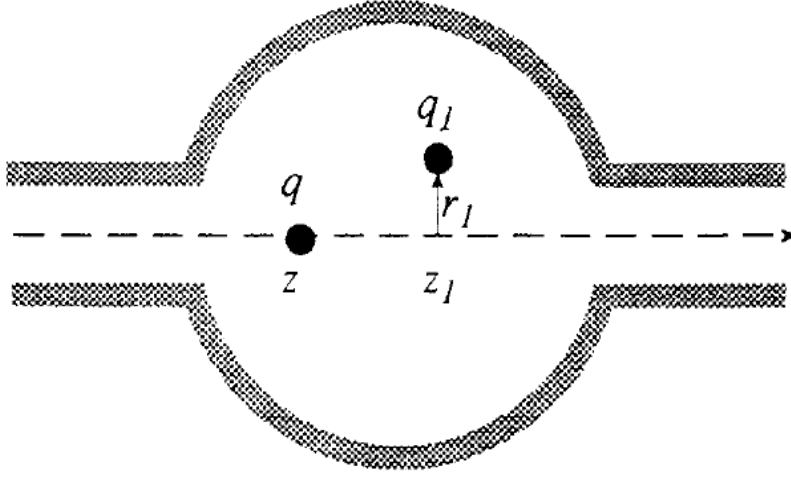


Figure 2.2

with $t = z_1/v + \tau$

This kick depends on the geometry of the structure in which the two particles are passing through and on the relative displacement between them. In the case in which the structure is presenting a cylindrical symmetry the resulting kick has a component only in the direction in which the kick is given: the two planes result then uncoupled, which simplifies consistently the analysis. This object is measured in Newton Meter $[Nm]$. As following from the longitudinal plane, now the previously mentioned equations can be translated in the transverse plane

$$k_{trans}(r_1) = M_{11}(r_1)/(q_1)^2, \quad (2.23)$$

$$w_{trans}(r, r_1; \tau) = M_{21}(r, r_1; \tau)/(q_1 q). \quad (2.24)$$

Considering that the dipolar term is the most consistent one in the expansion of the field components (in case of small displacement values) and knowing that the displacement is proportional to the dipolar kick, it is possible to define the transverse dipole wake function as the transverse wake per transverse displacement unit and the kick factor as the kick factor per transverse displacement unit

$$k'_{trans}(r_1) = k_{trans}(r_1)/(q_1)^2 r_1, \quad (2.25)$$

$$w'_{trans}(r, r_1; \tau) = w_{trans}(r, r_1; \tau)/(r_1), \quad (2.26)$$

Following the same procedure as in the longitudinal scenario it is possible now to define the transverse wake potential $[V^\circ C]$ and the bunch transverse loss factor $V^\circ C$

$$W_{trans}(r, \tau) = \frac{1}{q_1} \int_{-\infty}^{\infty} i_b(\tau') w_{trans}(r, \tau - \tau') d\tau' \quad (2.27)$$

$$K_{trans}(r) = \frac{1}{q_1} \int_{-\infty}^{\infty} W_{trans}(r, \tau) i_b(\tau) d\tau \quad (2.28)$$

and following the transverse wake and loss factor per unit displacement (assuming again a dominant dipolar component in the field decomposition)

$$K'_{trans}(r) = \frac{K_{trans}(r)}{r} \quad (2.29)$$

$$W'_{trans}(r, \tau) = \frac{W_{trans}(r, \tau)}{r} \quad (2.30)$$

The transverse impedance is defined as

$$Z_{trans}(r, r_1, w) = j \int_{-\infty}^{\infty} w_{trans}(r, r_1, \tau) \exp^{-j\omega\tau} d\tau \quad (2.31)$$

and its reverse, from which the wake function can be extracted back

$$w_{trans}(r, r_1, \tau) = \frac{j}{2\pi} \int_{-\infty}^{\infty} Z_{trans}(r, r_1, w) \exp^{j\omega\tau} d\omega \quad (2.32)$$

2.2.3 From Longitudinal to Transverse Wake function

A charge moving along the z axis with velocity v trough a electromagnetic field will experience the following Maxwell's equation components, expressed in cylindrical coordinates, where r is the radius, z is the height and ϕ the azimuthal angle.

$$F_z = qE_z, \quad (2.33)$$

$$F_r = q(E_r - vB_\phi), \quad (2.34)$$

$$F_\phi = q(E_\phi + vB_r). \quad (2.35)$$

The Maxwell's equations will give the following components

$$\frac{\partial E_z}{\partial r} = \frac{\partial E_r}{\partial z} + \frac{\partial B_\phi}{\partial t}, \quad (2.36)$$

$$\frac{1}{r} \frac{\partial E_z}{\partial \phi} = \frac{\partial E_\phi}{\partial z} - \frac{\partial B_r}{\partial t}, \quad (2.37)$$

and in a moving frame $\zeta = z - vt$ we derive

$$\nabla_{trans} F_z = \frac{\partial F_{trans}}{\partial \zeta}. \quad (2.38)$$

The moving frame has its origin in the position of the leading charge, where $\zeta = 0$. On the trailing one instead $\zeta = -vt$. Considering that we are taking into account the force on the trailing charge the derivation with respect to ζ can be replaced by the derivation with respect to τ

$$-\frac{1}{v} \frac{\partial}{\partial \tau} w_{trans}(r, r_1, \tau) = \nabla_{trans, r} w_z(r, r_1, \tau), \quad (2.39)$$

which is expressed in V/Cm . This is what is called the Panowsky-Wenzel theorem and it links the transverse impedance to the transverse gradient of the longitudinal one, where just the dipolar component is considered. From this latest equation by applying the Fourier Transformation it is possible to reach a simple expression, in terms of impedance

$$Z_{trans}(r, r_1, w) = \frac{c}{w} \nabla_{trans} Z(r, r_1, w) \quad (2.40)$$

This expression is literally providing the longitudinal impedance in terms of the transverse dipolar one and it represents the more common and used form of the Panowsky - Wenzel term.

Another useful expression in the coupling impedance world is the broadband resonator equation, which gives an approximation of the response in terms of impedance given by an excited resonant structure:

$$Z(w) = \frac{R}{1 + jQ(\frac{\omega}{\omega_0} - \frac{\omega_0}{w})} \quad (2.41)$$

This expression quantifies the contribution to the coupling impedance given by an High Order Mode (HOM) in terms of shunt impedance(R), quality factor(Q) and resonant frequency(f). By inserting this three parameters into the equation it is possible to compute the width of the relative peak and his effective amplitude, for one resonant mode or more of them.

2.3 Impedance evaluation in CST

In Computer Simulation Technology the procedure used to evaluate the coupling impedance consists in simulating a pencil test bunch with gaussian longitudinal profile passing trough a given structure and an integration path given by test charge following the leading one.

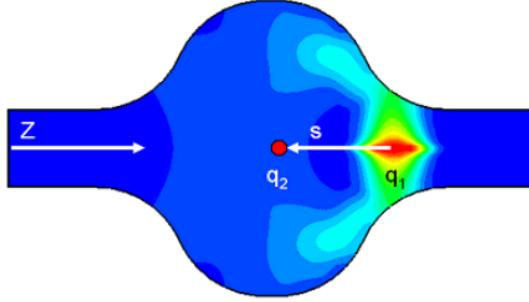


Figure 2.3. Leading charge exciting wake fields inside a resonant structure

The structure is divided into many mesh cells and once the proper boundary conditions have been set up Maxwell's equations are solved inside all the subdomains by taking the test bunch as source of electromagnetic field.

Starting from the wake potential equation

$$\vec{W}(r_1, s) = \frac{1}{q_1} \int_{-\infty}^{\infty} \vec{E}(r_1, z, t) + \vec{v}_z \wedge \vec{B}(r_1, z, t) dz \quad (2.42)$$

$$\vec{W}(r_1, s) = \frac{1}{q_1} \int_{-\infty}^{\infty} \vec{E}(r_1, z, t) dz \quad (2.43)$$

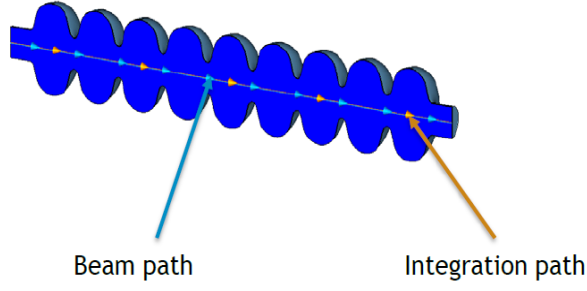


Figure 2.4. Integration path and beam path inside a structure

Now if it is considered that the tangential component of the electric field at the boundaries is vanishing it is possible to compute the transverse impedance by using Panowsky-Wenzel theorem

$$\vec{W}(r_1, s)_{trans} = -\nabla_{trans} \int_{-\infty}^s W(r_1, s') ds' \quad (2.44)$$

Now if it is considered as λ the normed charge distribution function over s the longitudinal and transverse coupling impedances can be defined as

$$Z_{long}(w) = \frac{\int_{-\infty}^{\infty} W(s) \exp^{-jws} ds}{\int_{-\infty}^{\infty} \lambda(s) \exp^{-jws} ds}, \quad (2.45)$$

$$Z_{trans}(w) = \frac{\int_{-\infty}^{\infty} W_{trans}(s) \exp^{-jws} ds}{\int_{-\infty}^{\infty} \lambda(s) \exp^{-jws} ds}. \quad (2.46)$$

Chapter 3

Measurement setup and Impedance evaluation techniques

During this thesis work many different tools and instruments were used in order to measure specific properties of different materials and to evaluate the coupling impedance. Different type of measurements were performed to infer the resistivity of a given sample under study: RF measurements, DC, measurements, Tune Shift evaluation with the beam, stretched wire measurements, observation with the scanning electrons microscope (SEM). The tools used are mainly CST and Impedance Wake 2D [1]. In the following paragraphs the measurements techniques will be explained in order to give an overview before passing to the results obtained in Chapter 4 and 5.

3.1 RF measurements on materials samples

The RF setup has been built in order to measure the resistivity of different materials by using the transverse impedance formulas: a probe with N turns has been connected to a VNA and then it has been placed in front of a sample to measure the electromagnetic coupling (Ref.[10]).

The distance between the block and the probe is arbitrary, as long as the field is passing through the desired material and it is not too attenuated. By elaborating the input seen by the VNA's ports and by applying the equations for a dipolar field it is possible to obtain a relation in which the dipolar impedance is expressed as a function of the signal seen by the VNA. If the wavelength is big compared to the length L of the DUT :

$$Z_y^{dip}(\omega) = \frac{j}{Q\Delta} \int_0^L (E(z, \omega) + c \times B(z, \omega)) dz \quad (3.1)$$

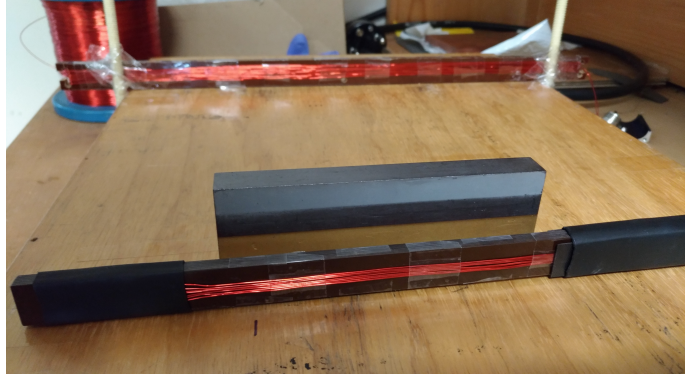


Figure 3.1. Example of a block produced for measurements

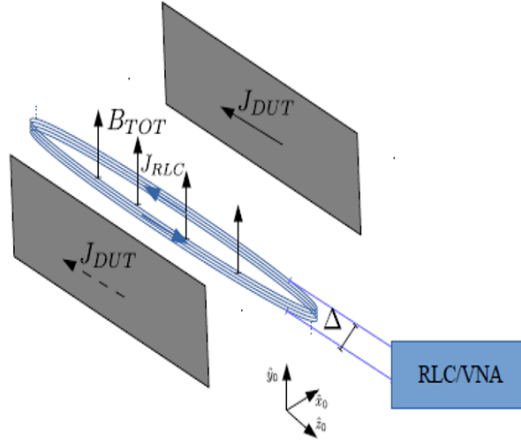


Figure 3.2. Scheme of the setup

The last equation in quasi-magnetostatic approximation becomes

$$Z_y^{dip}(w) = \frac{j}{Q\Delta} LcB_y(w) \quad (3.2)$$

Considering now that $V_{VNA} = I_{VNA} \cdot Z_{VNA} = jwB_y N \Delta L$ it is possible to obtain

$$Z_y^{dip}(w) = \frac{c}{w} \frac{Z_{VNA}}{N^2(\Delta)^2} \quad (3.3)$$

This last formula will then be applied to derive the transverse impedance of a given block with respect to a sample of the same size made of aluminum taken as

reference

$$Z_y^{dip}(w) = \frac{c}{w} \frac{Z_{VNA}^{block} - Z_{VNA}^{ref}}{N^2(\Delta)^2} \quad (3.4)$$

From this equation now with the help of IW2D, a simulation tool developed here at CERN, it is possible to infer the resistivity. This has been done by following the procedure expressed in the next diagram (Ref.[5]):

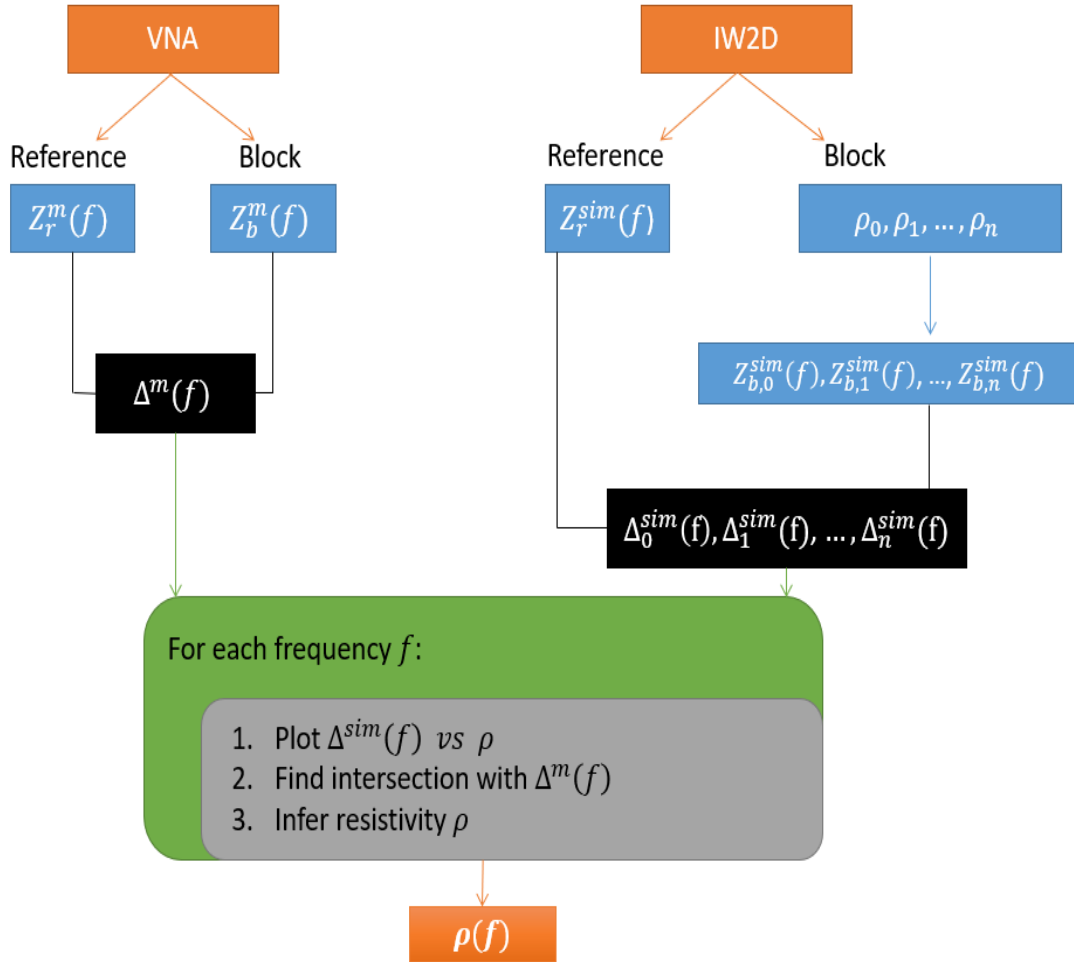


Figure 3.3. Flow Chart of RF measurements method

As reference, a block made of aluminum with the same dimensions of the sample to measure is usually chosen. The measurements performed with the VNA gives as result the $\Delta^m(f)$. With IW2D it is possible to simulate the transverse impedance of different blocks with the same dimensions as the measured samples but with different

resistivities. By subtracting these obtained values the different deltas for different resistivities can be computed. If now the deltas are plotted for different ρ together with the measured value

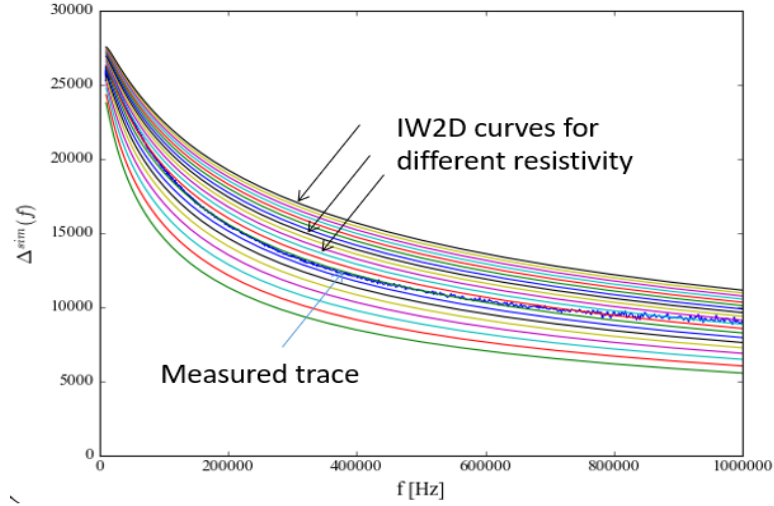


Figure 3.4

all the values of ρ can be selected and extracted for a frequency value, as following

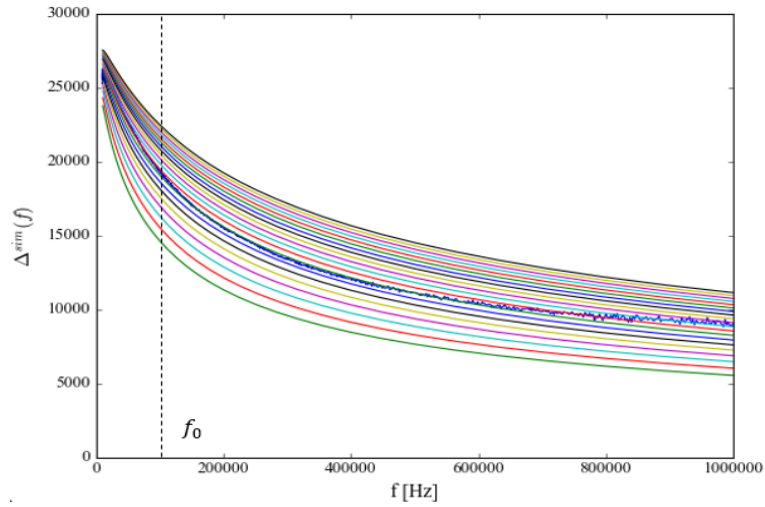


Figure 3.5

Once the frequency has been chosen the correspondent resistivity value is extracted:

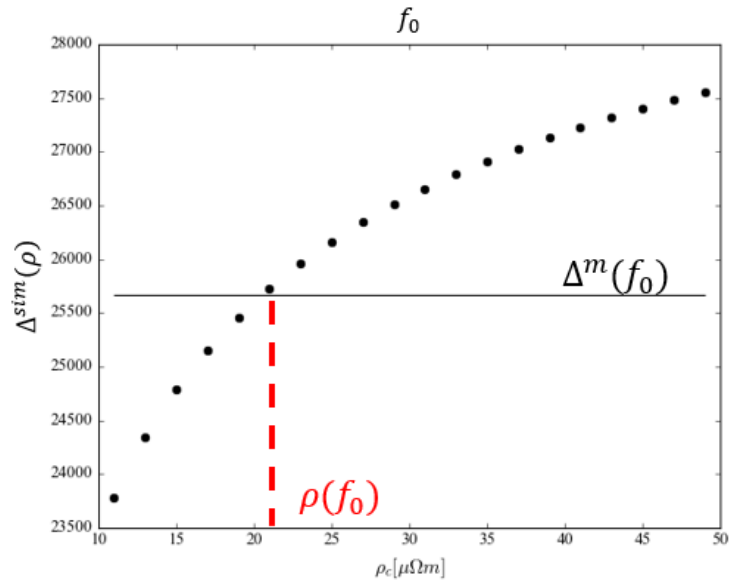


Figure 3.6

And by doing this for several frequencies it is possible to obtain the full range of resistivities vs frequency, as for example 3.7

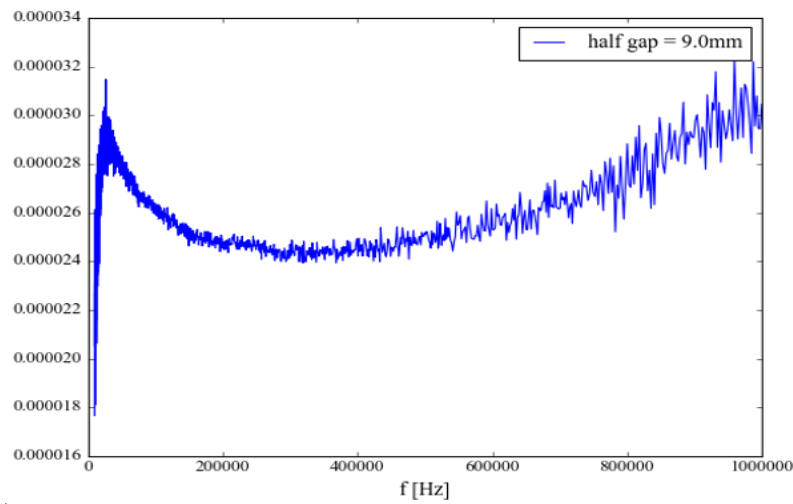


Figure 3.7

In this final plot all the results obtained are shown, resulting in a function which consist in the full resistivity range of the component.

3.2 DC measurements on materials samples

In order to infer the resistivity values of a given sample DC measurements were also performed to compare the results with what was obtained from RF measurements. The method used is an optimized 4-point probes method, where a current is flowing inside the sample and the voltage is measured at different positions.

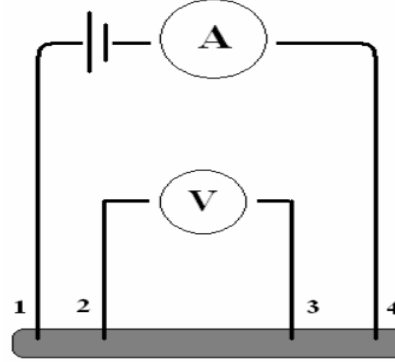


Figure 3.8. Four points measurement's method

The tools used during the session are shown in picture 3.9 by a current generator (1) a voltmeter (2) and a custom made accurate current reader (3) to cross-check the generated current. This last piece is necessary considering often the current flowing out the generator is not displayed with a good precision on his screens (Ref.[5]).

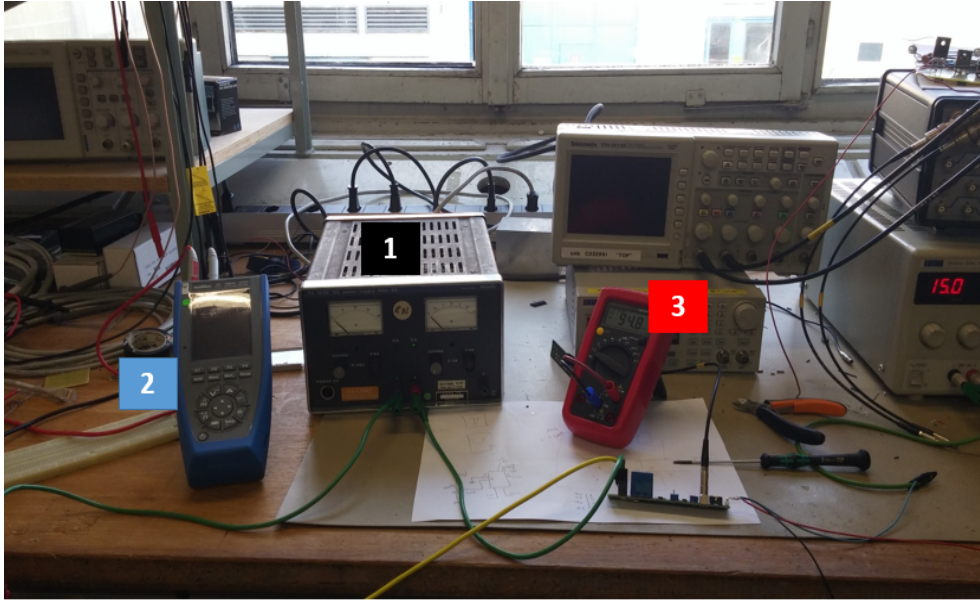


Figure 3.9. Picture of the setup

The sample to be measured is then pressed in a mechanical clamp with its two ends electrically isolated via insulating tape. The value of mechanical pressure is selected around 100 *N*. The electrical clamps of the current generator are connected

to two different metallic plates, placed between the block and the clamp's ends (Ref[5]), as shown in pictures 3.10 3.11

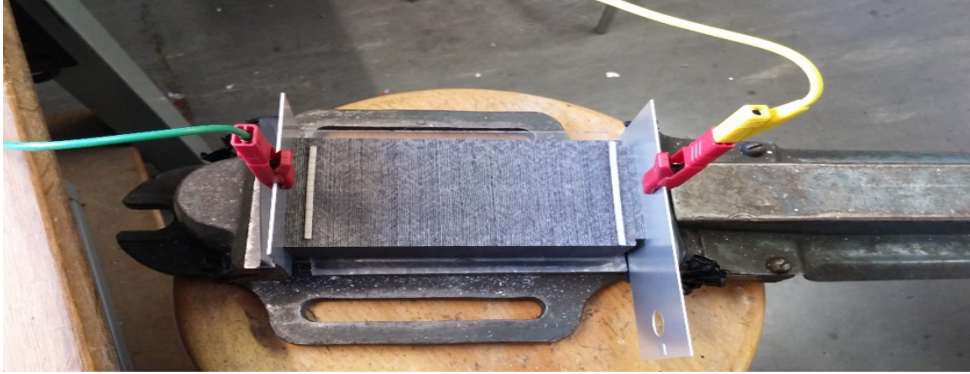


Figure 3.10. Block clumped between two plates

Two small sticky stripes of aluminum are placed on top of the sample to measure the voltage with the two voltmeter's pick ups. The setup was built in order to achieve a good current homogeneity inside the block: with a good distribution the voltage measured is more reliable and leads to more accurate results.

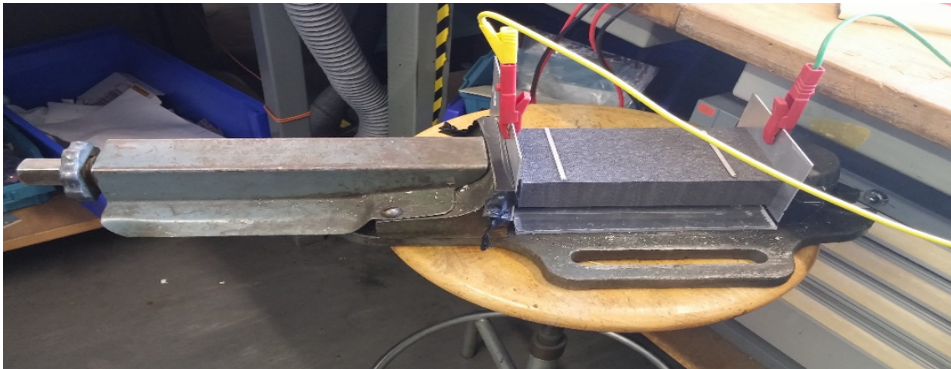


Figure 3.11. Block clumped between two plates

The procedure is then to measure the voltage for a specific position of the sticky bars for different current values: If there is a good linearity between V and I then the resistivity of the material can be inferred by applying Ohm's laws:

$$V = \rho \frac{L}{S} * I \quad (3.5)$$

where with L the distance between the two aluminum bars is intended, with S the cross section of the sample. Then the idea is to repeat the measurements for different stripes position, to achieve a good precision in the determination of the final results and to disentangle edge effects.

3.3 Resonant wire measurements

In the next chapters resonant wire measurements will be performed in order to infer the longitudinal impedance of a collimator. A metallic wire is passed through the device and each of its two endings is connected to a resistor in series with a capacitance. Then the two ends are connected to a VNA, in order to measure the S_{21} parameter (Ref[15]).

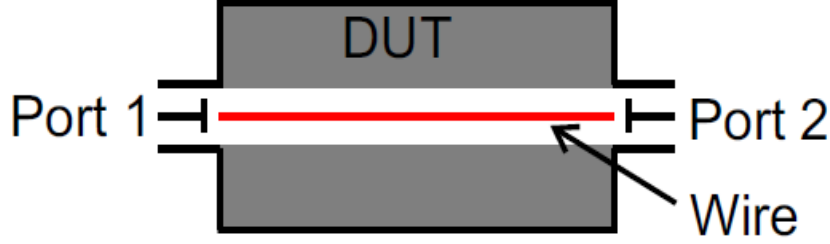


Figure 3.12. Wire passing trough the DUT

No matching is needed for this method. This capacitive coupling generated by the two capacitance is driving the structure into resonances when:

$$L = n\lambda/2 \quad (3.6)$$

where L is the length of the structure, λ the wavelength and n the number of the resonance. This method is presenting many advantages, amongst which a good precision and an immunity to spurious effects such as calibration uncertainties and instrument drift. The loaded quality factor Q_L of each resonance can be inferred and it can be used to calculate the line attenuation and thus the real part of the longitudinal impedance. The reflections are not considered in the Q_L at the first order, just the losses due to the materials inside the considered structure are measured: high precision is usually expected from this method. Starting from the coupling coefficient

$$k = \frac{|S_{21}|}{1 - |S_{21}|} \quad (3.7)$$

it is now possible to compute the unloaded quality factor Q_0

$$Q_0 = Q_L * (1 + k) \quad (3.8)$$

Now the line attenuation is defined as

$$\alpha_m = \frac{\pi}{\lambda Q_0} \quad (3.9)$$

and considering that a significant contribution to the line attenuation is due to the resistivity of the wires

$$\alpha_w = \sqrt{\pi\rho\epsilon}f \frac{1}{d \log \frac{D}{d}} \quad (3.10)$$

the corrected attenuation can be defined as

$$\alpha = \alpha_m - \alpha_w \quad (3.11)$$

where ϵ is the permittivity, ρ is the resistivity of the wire, d is the wire diameter and D is the outer conductor diameter. The real part of the longitudinal impedance is then given by

$$Re[Z] = 2Z'_L * \alpha \quad (3.12)$$

where the line impedance is defined as $Z_L/\Omega = 60 \ln(D/d)$ where D is the diameter of the structure and d the diameter of the wire.

Chapter 4

TCSPM impedance simulations and measurements

4.1 Overview

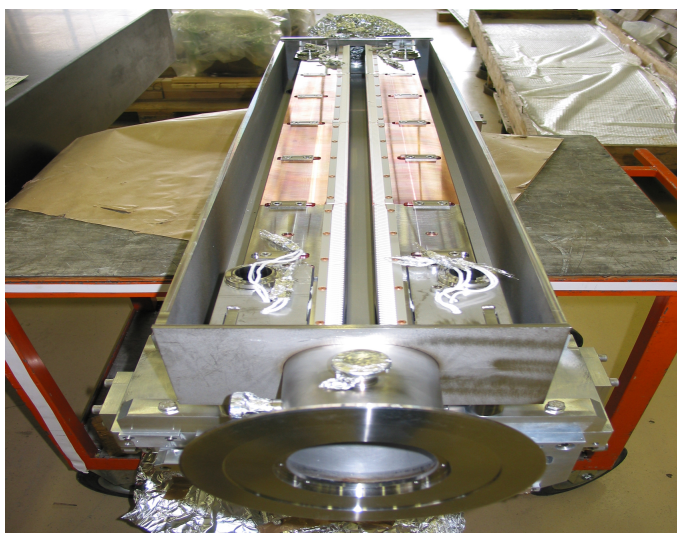


Figure 4.1. Top view of the collimator

The TCSPM is a multi stripe prototype collimator installed in the LHC. It belongs to the family of second generation secondary collimators (TCSPM, Target Collimator Secondary with Pick-Up Metallic) and it has been built using advanced materials that are conceived to reduce the collimator impedance while maintaining or even improving the jaw robustness against relevant beam failure scenarios. It has the peculiar characteristic of having three stripes made of different materials: the first one is made of Molybdenum Graphite (MoGr) bulk coated with Titanium Nitride (TiN), the second one made just of MoGr bulk, the third one made of MoGr bulk coated with Molybdenum (Mo). Since the LHC impedance is dominated by the contribution of collimators, in particular by the carbon-based primary and secondary ones, the TCSPM upgrade will reduce substantially the total machine impedance

(Ref.[14]). Purpose of this analysis is to fully characterize the collimator under the coupling impedance point of view, in order to understand what could be its impact on LHC beam losses and beam instabilities. Significant improvements are expected especially in operational scenarios with tight settings (6.5 sigma), in which the jaw's materials impact on resistive wall impedance is becoming the main impedance effect in LHC machine. Studies on geometrical features of it will also be performed in order to comprehend how the prototype could be improved in the future months in sight of HL-LHC project. In particular in the next sections the following studies will be performed:

- analysis of the contribution of different stripe's materials to the longitudinal impedance (resistive wall contribution)
- analysis of longitudinal and transverse impedance in case of lateral RF finger's failing (geometric contribution) This steps will be realized by means of:
 - Wire measurements on the component in the laboratory
 - Simulations with CST Particle Studio
 - RF measurements
 - DC measurements
 - Simulations with Impedance Wake 2D
 - Sigma-meter measurements
 - Tune shift measurements
- Further observations via Scanning Electron Microscope

4.2 Measurements and simulations of stripes contribution to impedance

4.2.1 Resonant Wire Measurements

One effective way to assess the resistive wall contribution of different materials is to measure the longitudinal impedance of the three different stripes with the wire resonant method. It should be kept in mind that the three stripes are made of three different materials: they give different contribution due to their different resistivity values (Ref.[9]).

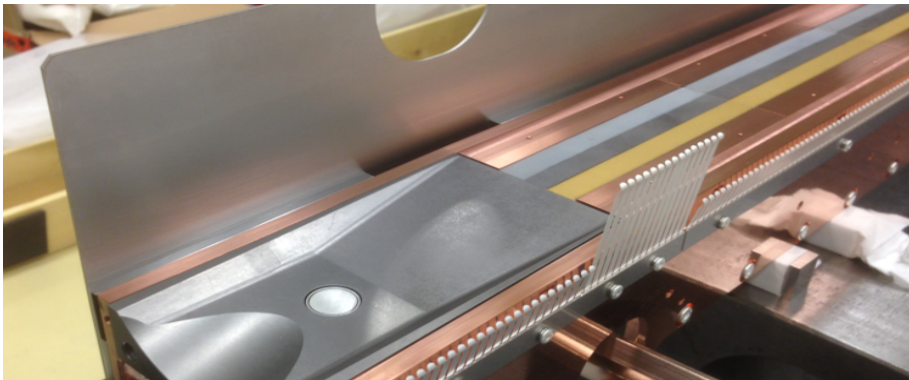


Figure 4.2. Top view of the three-striped jaw

A copper wire was passed through the structure without touching any border or

material in order to not damage the inside part of the collimator. Its two endings were connected to the ports of the VNA: this has been done in order to perform S21 and S11 measurements, from which by means of simple formulas it is possible to compute the longitudinal impedance for different wire displacement with the resonant wire method, assuming 5 mm as sampling step. Before the VNA connectors a little capacitance was installed on both sides: this is required in order to drive the wire into resonances from which the longitudinal impedance can be extracted as explained in Chapter 2. It is important to keep in mind that the integration path for the impedance computation is the same as the beam path: this is implicit in the measurements performed with just one metallic wire and this is why we could just measure the longitudinal contribution. The wire displacement's step has been

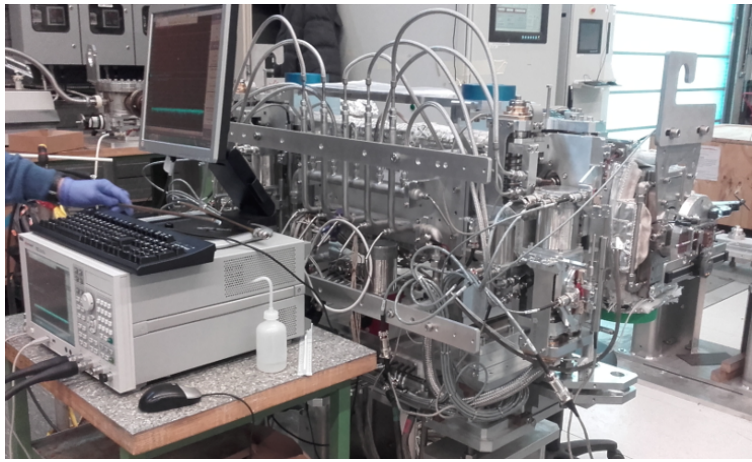


Figure 4.3. TCSPM test bench

defined with a reasonable compromise between resolution (each movement has to define a measurable quantity) and physical effort (the wire has to be displaced every time manually by means of a simple mechanism).

In fig 4.4 one can see the complexity of the internal part of the structure, with significant asymmetries in the horizontal plane. This is mainly due to RF fingers, a component whose purpose is to prevent geometrical discontinuities that are able to cause electromagnetic perturbations: this could be potentially dangerous in proximity of steps between components.

In the next pages it will be possible to see all the results obtained for different wire positions, with 5 mm half-gap jaw opening and at 76 MHz of frequency: The jaw aperture was chosen in order to detect as much as possible the resistive wall contribution to impedance (the closer is the material the bigger is the effect) while the frequency was chosen at 76MHz to avoid bumps due to resonant modes: at higher frequencies is really common to have trapped modes in complex structures as this one, they could easily affect the broadband behaviour if they are close to the chosen frequency for measurement.

The displacements along X axis have been performed with a step of 2mm and the results will be plotted as S21 parameters already converted into longitudinal impedance versus frequency. It must be kept in mind that the width of a single stripe is 10mm, which yields to the following pattern:

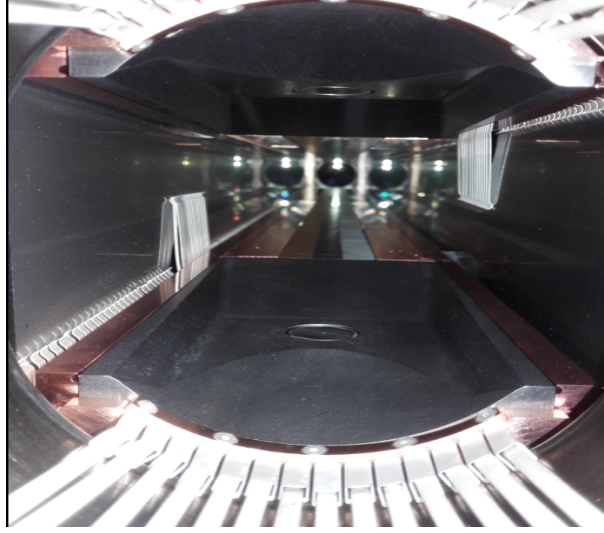


Figure 4.4. TCSPM inside view

from -30 to -15: Copper annealed
 from -15 to -5 mm : MoGr coated with Tin
 from -5 to + 5 mm : MoGr bulk
 from +5 to +15 : MoGr coated with Mo
 from +15 to + 30: Copper annealed

Table 4.1. Materials resistivity

TiN	MoGr	Mo
4e-7 Ohm.m	1e-6 Ohm.m	5.35e-8 Ohm.m

In figure 4.5 all the results have been plotted versus the displacements. It can be seen that the impedance has a strong dependence on the position of the wire due to the resistive wall effect given by material with a finite conductivity: the larger it is and the more significant contribution should be seen in the longitudinal impedance. Another important observation about the plot is that judging by the resistivities in 4.4, the behaviour expected should represent a reversed parabola, especially considering the difference of orders of magnitude with MoGr coated with Mo and MoGr coated with TiN: this is not happening in the measurements performed, the impedance measured in proximity of MoGr bulk presents a lower value compared to what expected. This could be due to different reasons and it requires more studies and simulations to be further investigated. The possible explanations to this behaviour could be:

1) Contribution to longitudinal impedance given by the transition tapers at the beginning and the end of the collimator(4.2). This could be further investigated by simulating the geometrical contribution given by metal smoothening at the beginning

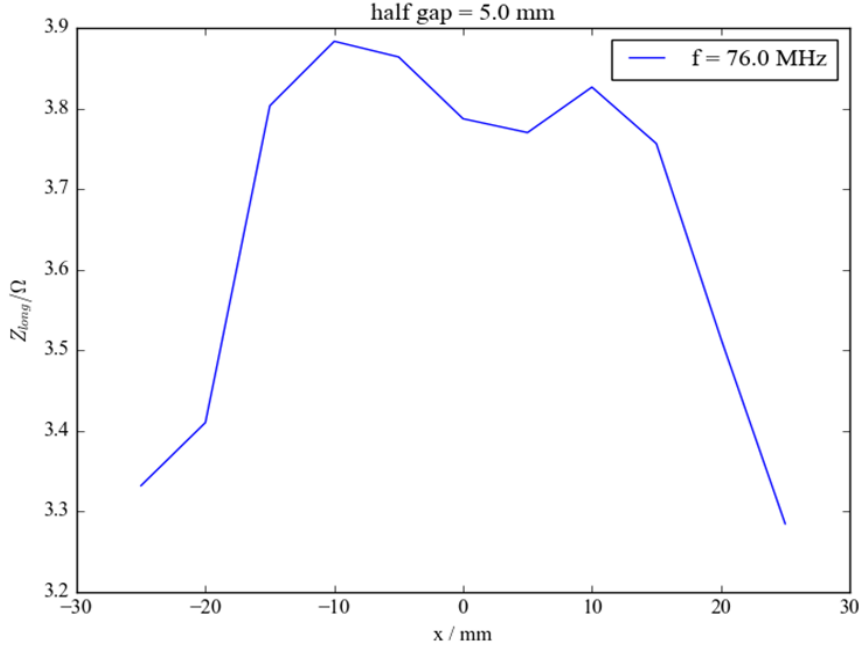


Figure 4.5. Longitudinal Impedance vs wire displacement along horizontal axis

and the end of the collimator. It is not known if this type of component is able to affect the results at that frequency, to be investigated.

2) Line Impedance of the coaxial system changing when moving the wire.

$$Z_L = 60 \log \frac{D}{d} \quad (4.1)$$

The not perfect centering could lead to a virtual changing of the diameters ratio, changing the value of the characteristic impedance and leading to unprecise results.

3) Wire non perfectly on the center of the structure, (little offset along y axis possible). This could lead to contributions due to a forced asymmetry generated by the unwanted displacement.

4) Different material properties from what expected from previous measurements sessions.

5) Issues with coating measurements as they are often tricky to deal with, the error could be due to the thickness of the layer that is in the order of magnitude of micrometers.

This problem has been addressed in many ways, searching for a possible reason for this discrepancy. The previously mentioned issues were investigated one by one and at the very end an explanation has been found. For brevity not all the studies will be explained, only the conclusion will be reported in this thesis work.(Ref.[12])

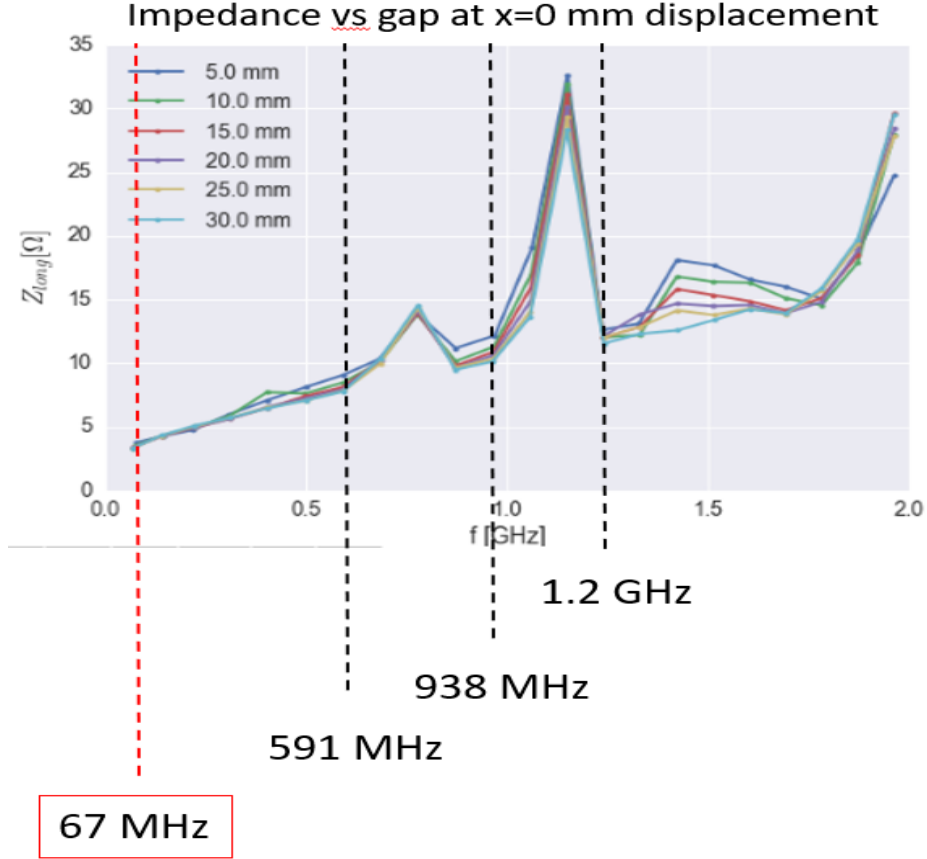


Figure 4.6. Impedance vs gap for X=0

In picture 4.6 all the different measurements were plotted for different half gaps apertures. This plot should contain all the values obtained for all the displacements for each gap: considering the significant number of points for simplicity just the scenario with the values obtained in X=0 has been reported. From the plot it is possible to select the frequency where the issue related to the materials have been spotted, around 70 MHz.

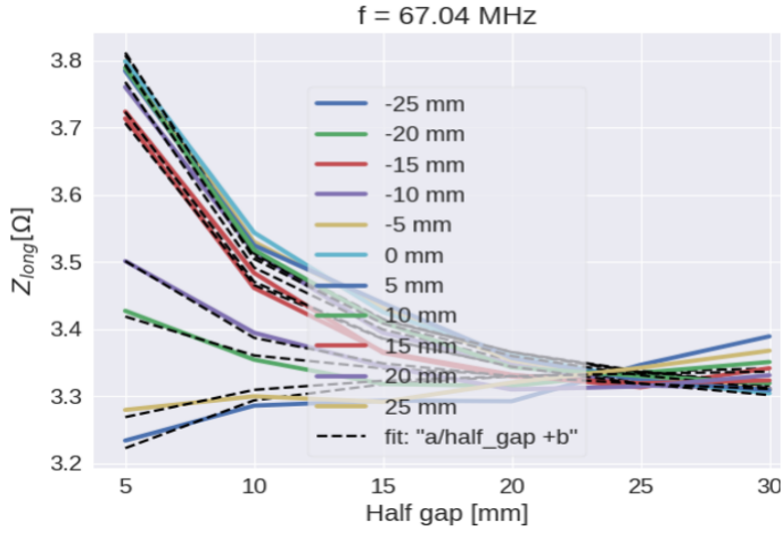


Figure 4.7. Fit performed for different displacements

The values can then be then plotted again as longitudinal impedance vs half gap position, for different wire displacements: now remembering that the resistive wall contribution is proportional to $1/\text{gap}$ a fit in dashed line has been performed on each function. This fit proportional to $1/\text{gap}$ is able to remove the geometrical contribution present in the collimator's jaws, leading to a clean resistive wall function's plot.

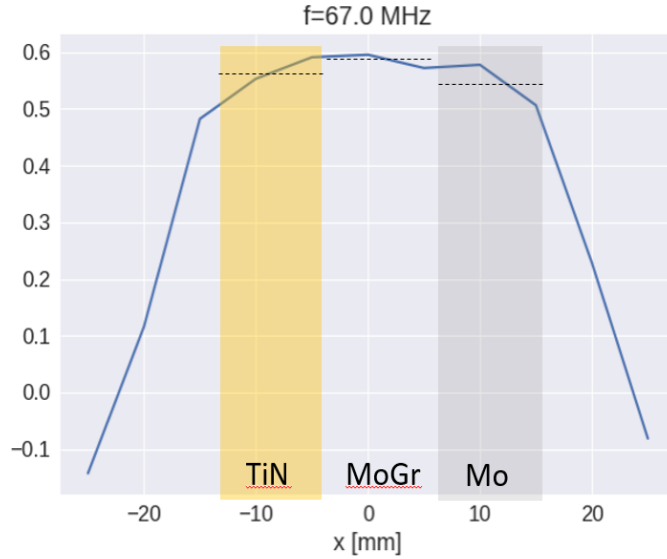


Figure 4.8. Results obtained after the fit

The trend is now clear and the expected properties are now shown. Thanks to the fit the other contributions which were affecting the wire measurement have been

eliminated, leading to a function totally dependent just on the properties of the different materials.

4.2.2 Simulations on TCSPM collimator

In order to further analyze the structure now IW2D will be used to perform simulations. This tool can prove useful when a 2D structure has to be studied. In this case the collimator's jaws, whose resistivity we want to evaluate, can be approximated by two infinite parallel blocks. The model of a two-layer three-stripped jaws was built preserving the original thickness and width of the components: despite the infinite length required by the code the contribution to impedance is evaluated per unit of length, so this constraint won't affect the results.

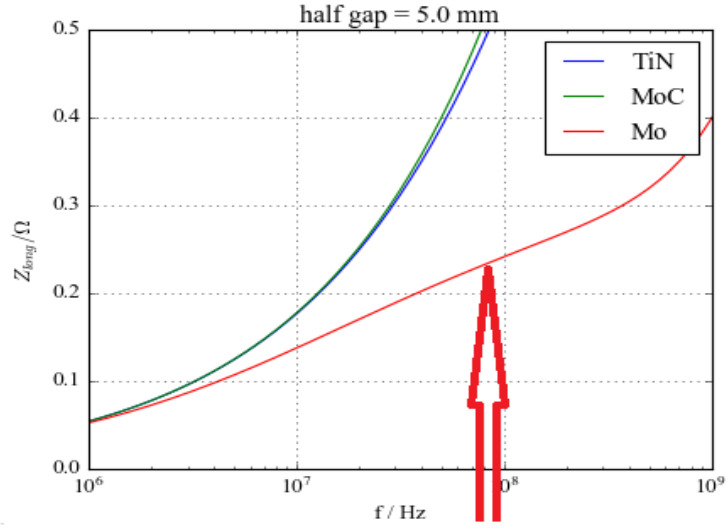


Figure 4.9. IW2D simulation on 2D structure

In this plot again all the simulation results are shown. What can be seen from the graph is the gap between MoGr and the other materials, as expected from the conductivity values. The longitudinal impedance values obtained show the same behaviour as in the resonant wire measurements, there are just some discrepancies in the numbers: this can be due to the fact that the code is simulating a perfectly 2D structure while in reality there are some imperfections in the materials composing the jaws.

In order to further analyze the structure the idea now is to approach it by means of CST: with this software it is possible to evaluate the coupling impedance of a given model built appositely by using its wakefield simulation solver. The model used for simulations has been imported from CERN mechanical design storage via CATIA (Ref[5]) and all its negligible features from electromagnetic point of view have been removed. The original model is shown in picture 4.10 in all of its complexity.

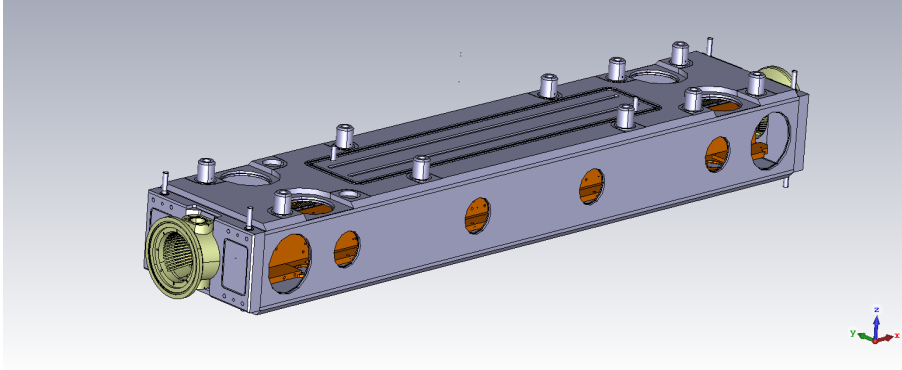


Figure 4.10. TCSPM original model

Importing all the features of the original model is almost impossible as it would take a considerable amount of computational power: in order to compute the wake-field response of a given structure CST solves Maxwell's equations inside meshcells by taking the selected bunch distribution as a source of electromagnetic field. This procedure with complex geometries could lead to large mesh numbers, which implies the use of many Gigabytes of RAM and a significant computational time to solve the equations set: with all this power it could happen to fall into an unstable simulation. Another significant reason to avoid to mesh the full structure is the negligible impact of all the components outside the vacuum chamber when the field is strictly confined into it.

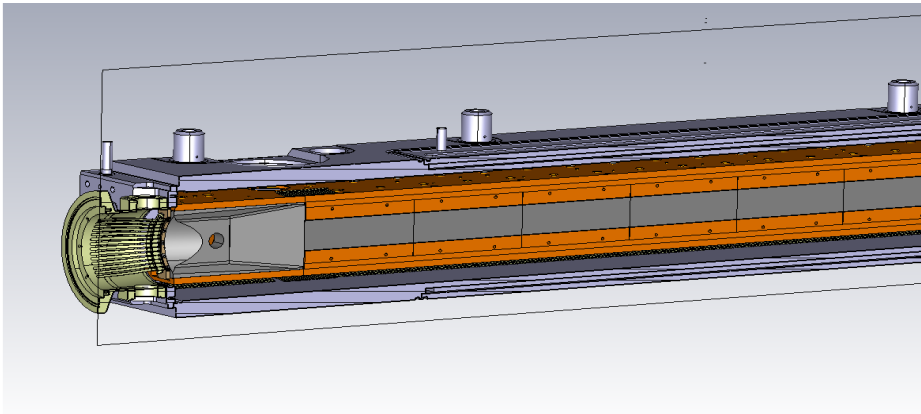


Figure 4.11. section of TCSPM (1)

Looking at the structures it is easy to notice all the features in its interior part, like RF fingers at the very beginning of the model and the structure tapering applied in the connection point between fingers and jaws. Tapering a structure is very

important operation done in order to avoid steep discontinuities between the access pipe and the jaws: it is able to prevent strong localized electric field patterns that could lead to overheating issues linked to significant power losses.

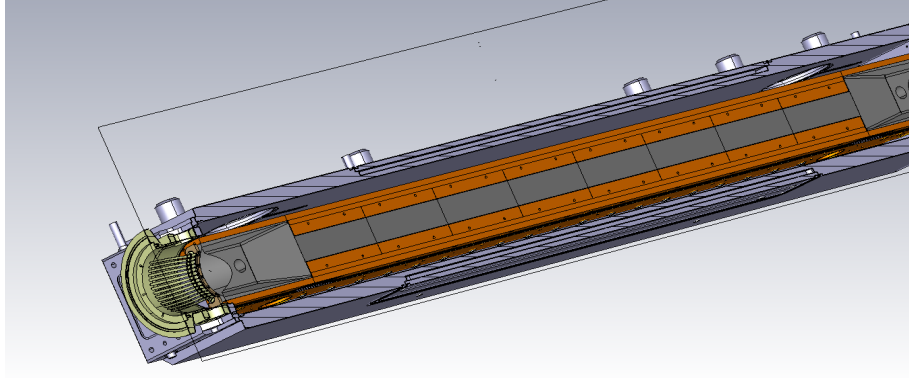


Figure 4.12. section of TCSPM (2)

RF fingers are another important feature created in order to deny possible field leaks between the beam pipe itself and the outer part of the collimator, they are useful because of the possibility they offer to electromagnetically insulate specific portions of a given structure from others.

Once removed all the negligible parts from coupling impedance point of view, the new CST model acquires a more friendly aspect, as shown in picture 4.13 :

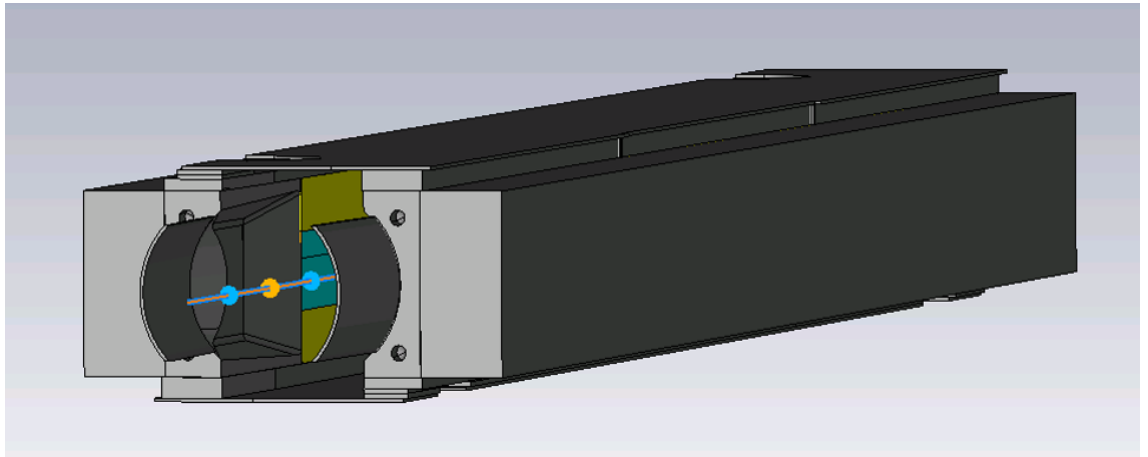


Figure 4.13. TCSPM simplified model

In this new version the following main features have been imported from the original structure:

- Transition tapers 4.14
- RF fingers 4.35
- bulk materials 4.16

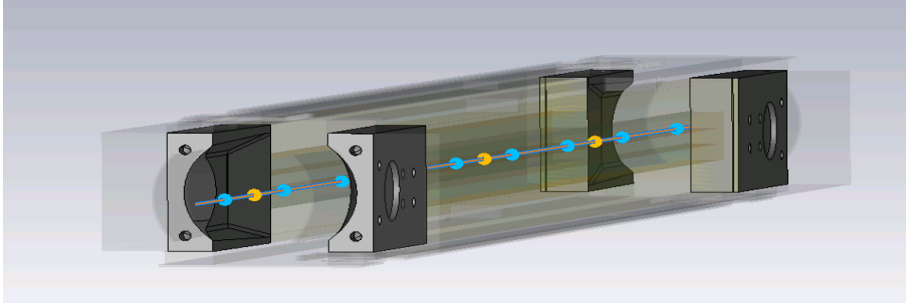


Figure 4.14

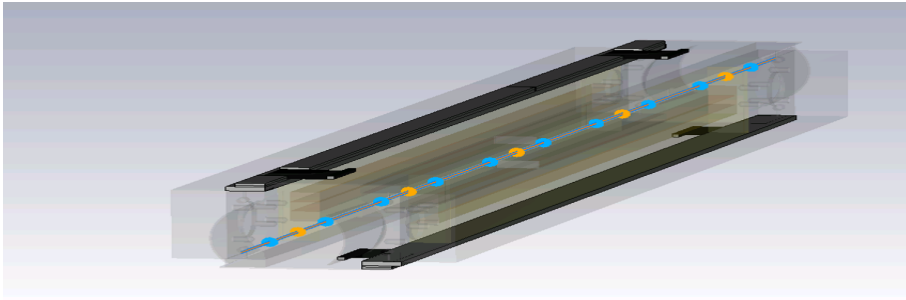


Figure 4.15

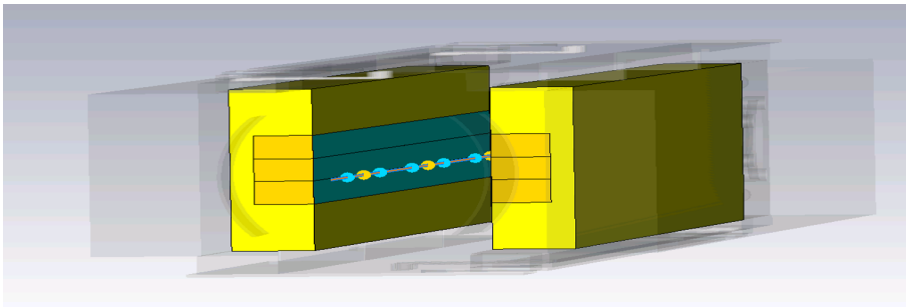


Figure 4.16

All the previous features were considered in order to simulate a reliable model of the original structure. The materials are the same of the installed TDIs: jaw envelope made of copper with $\rho_{DC} = 5.96e-7 \Omega * m$ and the three bulk jaws with

the resistivities mentioned in table 4.4 The results obtained are reported in 4.17 The displacement step this time was set to 2mm, in order to increase the resolution obtained. The frequency is again 78 MHz.

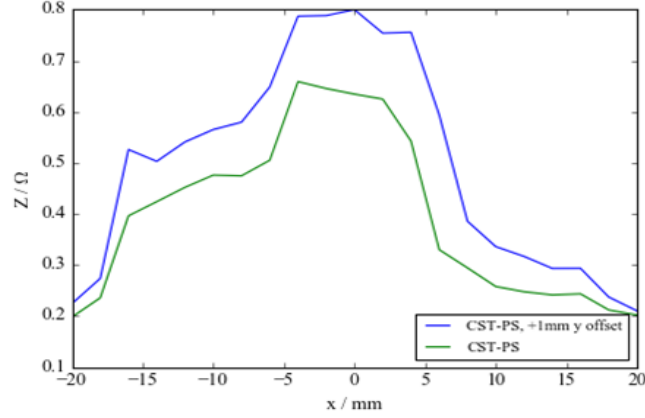


Figure 4.17. Longitudinal impedance vs horizontal displacements

In the plot the beam was displaced also beyond the three stripes, on raw copper, the material composing the envelope of the jaws. The results for this run with the beam perfectly centered are plotted in green.

As noticeable from the plot the impedance is behaving in a quite physical way by following the resistivity variation along different materials: the step transition happens when passing from a stripe to the other, resulting in a steep decrease in longitudinal impedance. This is exactly the behaviour expected from the materials under study, in good agreement with what was expected from theory.

The blue line is showing the results obtained in the case in which the source has a slight offset on the opposite axys (y). This means that the wire is moved not in the direction in which the material around it is changing but in the opposite one, where the material is not changing.

$$Z_{trans}(\omega) = \frac{c}{\omega} * Z_{long}(\omega) \quad (4.2)$$

Deriving from Panowsky-Wenzel Theorem (chapter 2) the longituinal impedance should have a quadratic relation with the displacement along a given axys: the blue plot in fact shows an offset given by the displacement along y, accordingly to Panowsky-Wenzel relation. This is something that usually is able to affect the results obtained with the resonant wire method, it is quite common to have a slight offset produced by a misalignment error at the very beginning of the measurement setup. As visible from the plot a slight wire error can lead to significant differencies in the impedance values, but the mistake is manifesting himself under the shape of a global offset, which is easily detectable by eye: this is not able to lead to a significant decrease in the longitudinal impedance measured in proximity of MoGr bulk and it is hence not able to modify the shape of the function itself. It has been then shown how much a small misalignment error could affect the reliability of the results.

4.2.3 RF, SEM, DC and Sigma Meter measurements

The coupling impedance is an electromagnetic property of a given structure which is strictly connected to the resistivity of the materials composing it. Purpose of this section is to measure the resistivity of the three different stripes composing the jaws of the TCSPM, in order to asses with the highest possible precision their expected resistive wall contribution (Ref.[11]). In order to achieve more informations about this property a sample of Molybdenum Graphite was produced with specific dimensions and coated with two different materials on the edges, Molybdenum (gray) and Titanium Nitride (yellow), represented in picture 4.18.

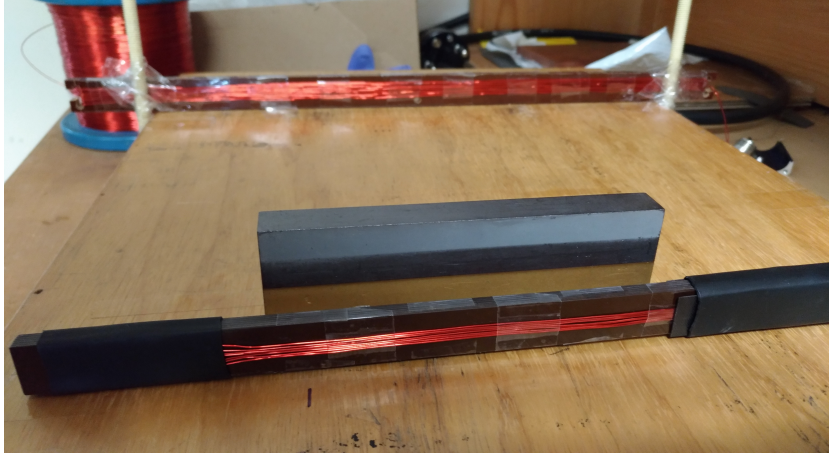


Figure 4.18. The sample made for measurements

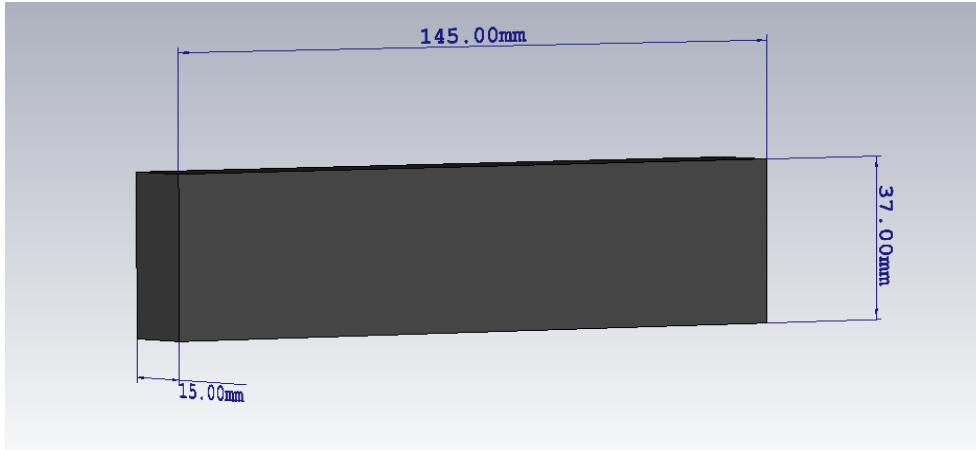
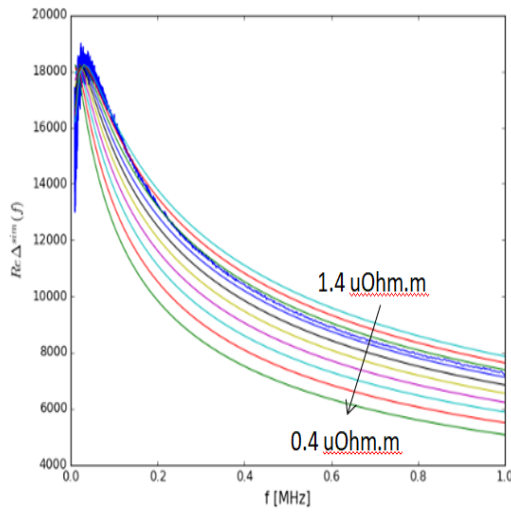


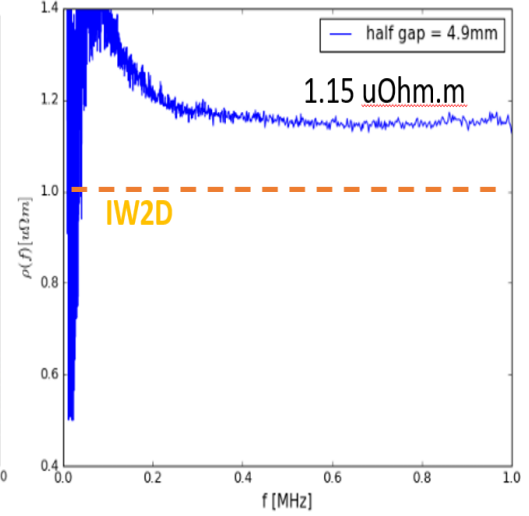
Figure 4.19. Dimensions of the sample

In the presented sample the molybdenum coating has a thickness of approximately 8 micrometers, the titanium nitride coating has a thickness of approximately 5 micrometers. The setup and the method used for the measurements have been illustrated in chapter 3 in the RF measurements section. The block was put in front of the coil in different positions in order to acquire different data from the three different stripes: each stripe is giving a different resistive wall contribution to the

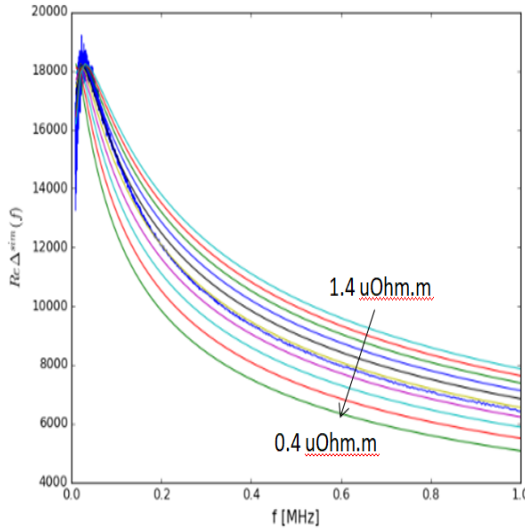
transverse coupling impedance and this is something which needs to be studied separately for the three different scenarios. Considering that the measurements on the block are strongly dependent on the differences between the distance of block's position with respect to coil's one, two spacers of 4.9mm were used all along the sessions. The first step in order to achieve the most accurate results possible with the tools available was first to measure the resistivity of the MoGr bulk behind the two different stripes: this value will be then used to simulate the resistivity of the two coatings by inserting it into IW2D for the simulations. The more reliable the value inserted the more accurate the results obtained in principle. Following the results for MoGr bulk:



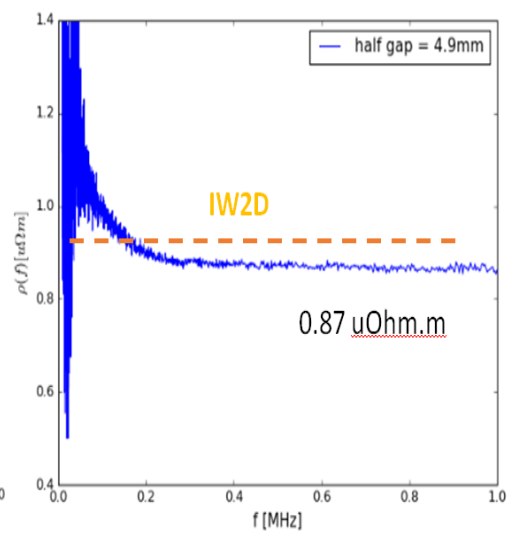
(a) MoGr bulk behind Mo



(b) MoGr bulk behind Mo



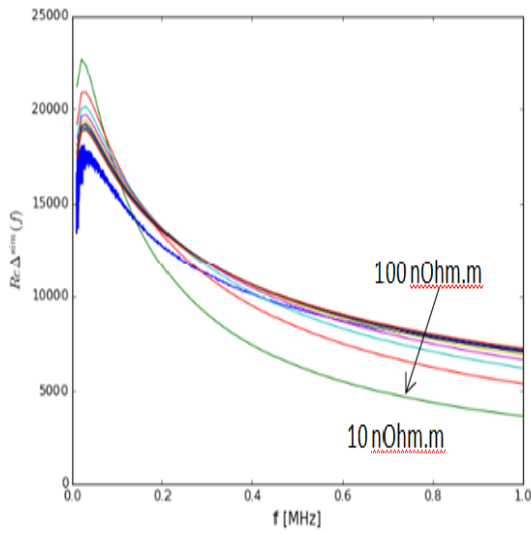
(a) MoGr bulk behind TiN



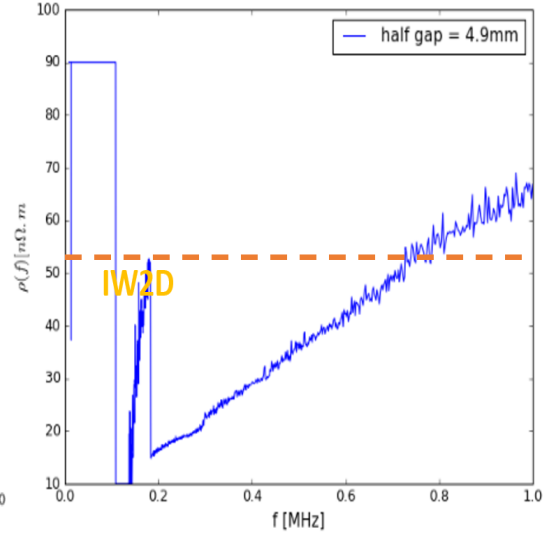
(b) MoGr bulk behind TiN

In plots 4.20a 4.20b the resistivity measured is above the estimation given

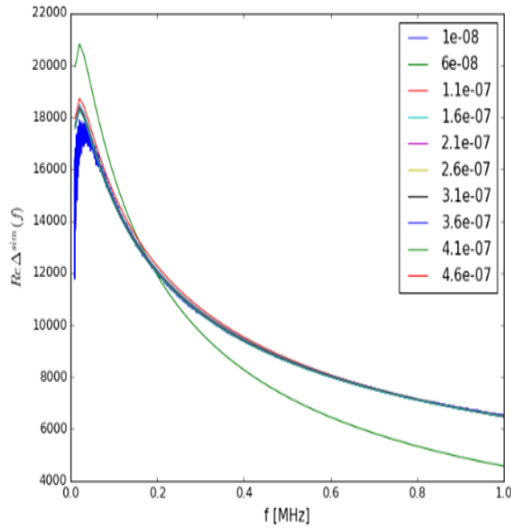
by IW2D. The behaviour of the resistivity is a exhibits an overshoot in the region below 0.2 MHz because of the field distribution, which is largely passing trough the block due to the skin depth of the material in that span of frequencies. After 0.2 MHz the resistivity starts to be a flat line, resembling the physical behaviour expected at "high" frequencies. In plots 4.21a 4.21b the resistivity of the block behind the TiN coating it is shown to be smaller than the one expected from IW2D code, which confirms the hypothesis of MoGr inhomogeneity. The behaviour in plots 4.20a 4.20b is then the same except for a slight offset. Now in order to determine the resistivities of the two coatings the two previously obtained values will be used to infer the the ones of Titanium Nitride and Molybdenum, as follows:



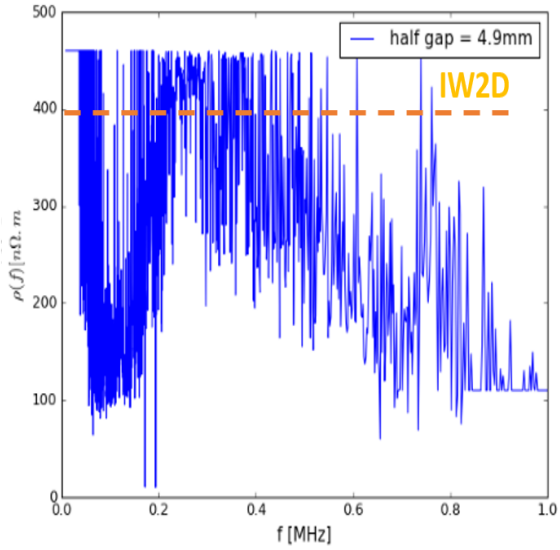
(a) Molybdenum Coating



(b) Molybdenum Coating



(a) Titanium Nitride Coating



(b) Titanium Nitride Coating

The results obtained in plot 4.22a in the evaluation of Molybdenum resistivity show that there isn't a good match between the simulated curve and the estimated ones. In fact at very low frequencies the measured curve in the plot is below the simulated ones, resulting in a bad mismatch below 0.2 MHz. After 0.2 MHz it is possible to define a measured resistivity in the expected range, between 20 and 100 nOhm*m, with an average value close to the one given by IW2D. Another issue visible from the plot is the drift in the resistivity function, which is literally increasing with the frequency, leading to unknown values after 1 MHz. These discrepancies haven't been solved yet: they could be due to the fact that the simulated block has been modelled as a perfect 2D structure made of a bulk with coating on top while the measured one is not a real 2D model, as shows the roughness and the imperfection of a typical coated material 4.24 4.25.

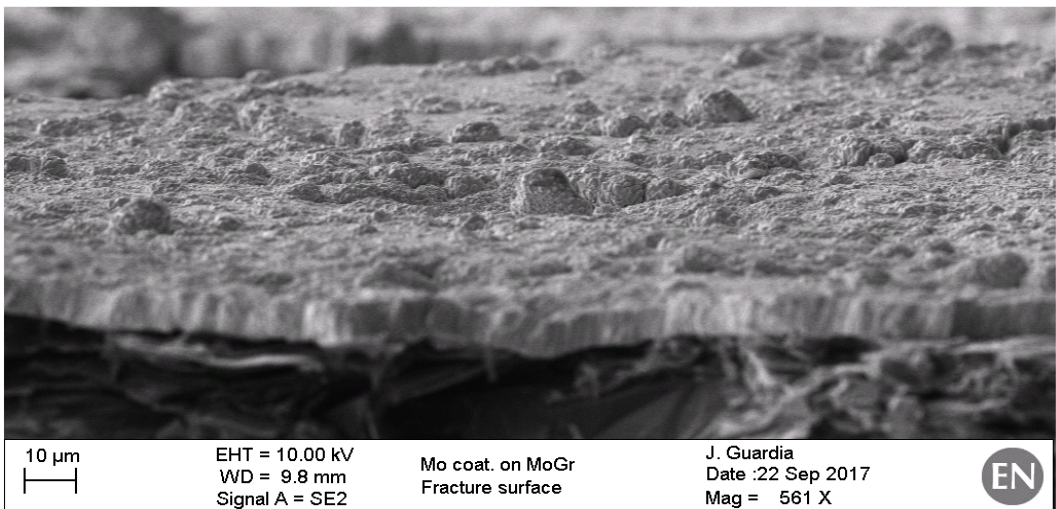


Figure 4.24. Mo coating scanned with SEM(Courtesy of J. Guardia)

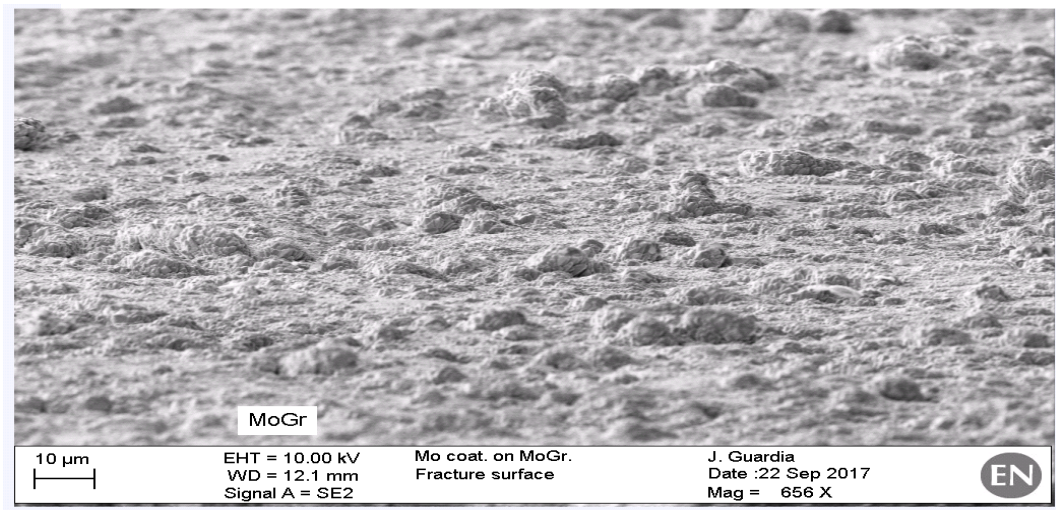


Figure 4.25. Mo coating scanned with SEM(Courtesy of J.Guardia)

These images have been produced using a Scanning Electron Microscope (SEM) in order to further investigate the discrepancy previously mentioned. (Ref[3]) This device is able to zoom in 38500 times, reaching at most the scale of nanometers (10-20). By taking a closer look at the Mo coating with a x656 zoom it can be seen how the surface isn't smooth: many imperfections are present on top as tiny mountains or small spheroids.

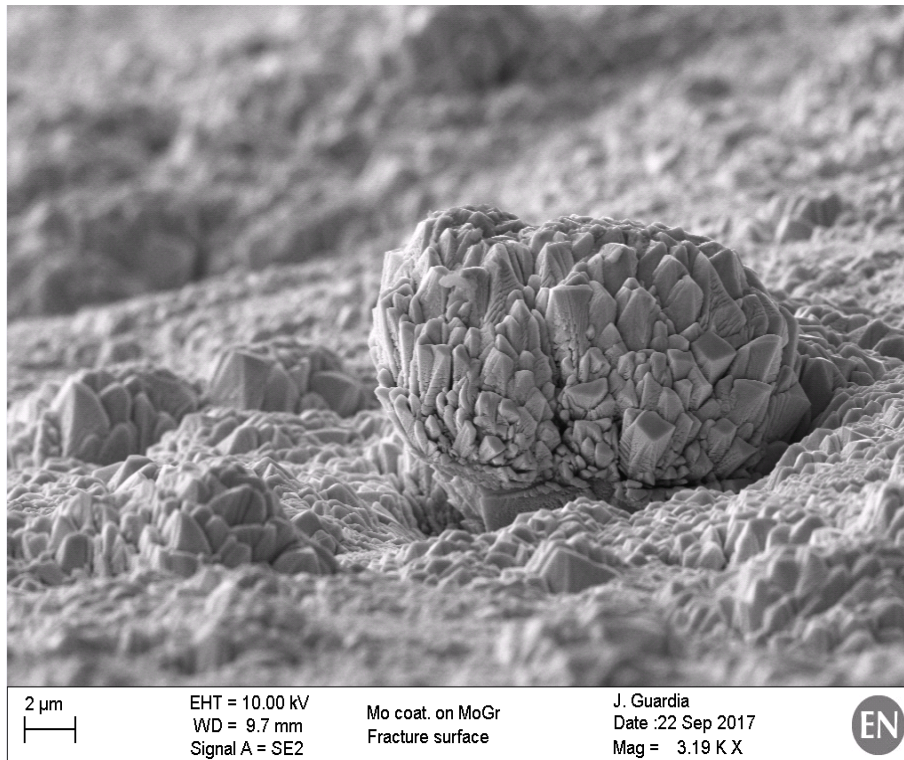


Figure 4.26. Courtesy of J. Guardia

The dimensions of these elements is not negligible before, these mountains can reach a not negligible size: sometimes they could even have the same height of the coating itself. In picture 4.26 a better zoom has been performed: this imperfection is measuring almost 8 micron, which is the thickness of the coating itself. This was something unexpected, especially considering the quantity of this undesirable features present on the surface: usually the accepted tolerance is around 1 or 2 microns. The imperfections are then making the measured block quite different from the 2D one simulated and this could explain why the simulated curves are that different from the measured one.

For what concerns the TiN coating what has happened is quite different from the scenario with Mo coating, in this case it is clear how the measured curve is matching too many simulated curves at the same time: The Titanium has a resistivity similar to MoGr's one, which implies that it is not easy to detect differences between the different curves plotted for different coating resistivity's values, leading to the result

plotted in curve 4.23a. The function is then not inferring a precise value of resistivity but it is giving a span of values in which the resistivity will be, in this case between 100 and 500 $\mu\text{Ohm}\cdot\text{m}$, which in any case is compatible with the order of magnitude given by IW2D's repository.

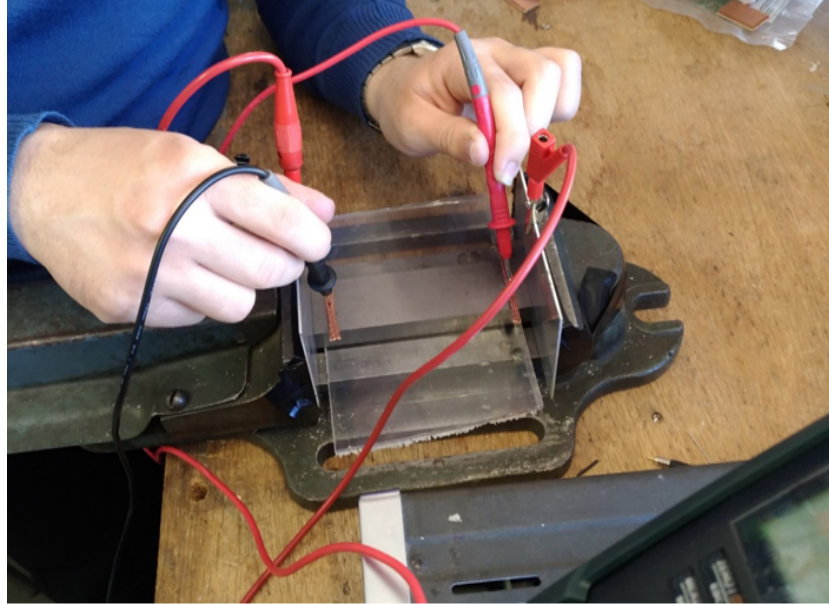


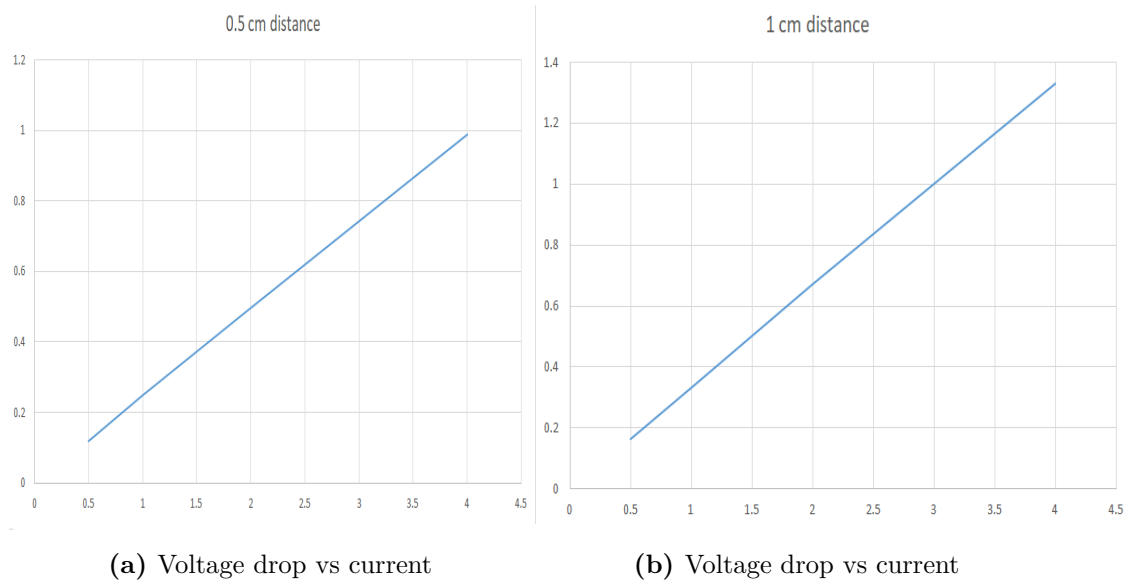
Figure 4.27. DC measurements

Also DC measurements were performed on the sample, in order to cross-check and match the obtained results (Ref.[11]). Due to the thickness of the two coatings the only measurable material was the MoGr bulk, which has a thickness compatible with an uniform distribution of flowing current. The sample was measured before coating it. The results are shown in the following tab:

Current [A]	Voltage Drop (mV)	
	0.5 cm distance from edge	1cm distance from edge
0.5	0.163	0.119
1	0.33	0.25
2	0.67	0.499
4	1.33	0.99
Resistivity [$\mu\text{Ohm}\cdot\text{m}$]		
	1.57	1.26
	1.59	1.32
	1.62	1.32
	1.60	1.31
Mean Value	1.60	1.30
Standard Dev.	0.02	0.03

Figure 4.28

In this context different measurements were performed for different copper bars displacements from the edge in order to improve the reliability of the results. The current was produced via a current generator and it was increased from 0.5 A to 4 A. The measured values represent the potential drop between the two copper bars, for different distances from the edges and different current values: from those one can extract the resistivity of the material via Ohm's laws if good linearity is obtained.



The inferred resistivity's average is reported for both cases in the tab 4.28, in green: as visible from those the resistivity is changing a bit between the bars at 0.5 cm of distance from the edge and 1 cm of distance, which shows again the non-homogeneity of the material. The results are in any case compatible with the ones obtained in the RF measurements session.

Another tool used to characterize the properties of the sample was the Sigma Meter, a device which is able to directly infer the resistivity of a given material by just putting in contact its sensor with the sample itself.



Figure 4.30. Sigma meter sensor on top of the block

The measurements were carried out on the the block with just one side coated with Molybdenum due to the availability of the instruments itself. In the following table the results are shown:

Results with Sigma Meter [MS/m]

Side A	Side B	Side C
1.111	0.97	1.021
1.061	0.9719	1.021
1.062	0.9708	1.021
1.032	BORDER	1.004
1.033		1.004
1.033		1.003
1.027		
1.016		
1.017		
1.022		
1.022		
Avg	Avg	Avg
1.040	0.971	1.012
0.028	0.001	0.010

Figure 4.31

The three letters represent the three longitudinal sides on which the measurements have been performed, the results inside the "border" part of the tab represent the measurements done on the border in green in picture 4.30. From this table it is possible to understand how at 960 kHz the effect of the coating itself is something not much visible, in fact the conductivity measurements are close between each other. This is due to the skin depth of these materials at low frequencies: the field is mainly passing through the Molybdenum coating and it is penetrating inside the MoGr bulk. Because of this effect the results are not distinguishable when passing from a stripe to the other.

The only difference that could be noticed is that even at low frequencies the coating is at least increasing a bit the conductivity measured by the sigma meter. Another noticeable thing is again the material inhomogeneity, which has been also noticed in RF and DC measurements: this property leads to different results in stripes B and C, where just the bulk made of Molybdenum Graphite is measured.

4.2.4 Measurements with beam

In certain cases special measurement sessions are allowed to be performed by using the LHC itself. These sessions are called Machine Development (MD) and they have been conceived to deeply understand the behaviour of the accelerator in specific conditions (Ref.[14]). In order to determine the effective resistivity of the previous mentioned materials composing the TCSPM tune shift measurements have been performed on the TCSPM prototype installed in the machine. These measurements are performed by injecting inside the machine different bunches with different intensities. By means of a kicker (which is in this case also a transverse damper) it is possible to kick a selected bunch in order to measure the machine's tune shift: this operation is done while the jaws of the TCSPM are moving from an open position to a close one, for different beam's position (the beam is usually displaced to pass below different stripes of material). The tune shift is strictly connected to the dipolar transverse impedance, as shown in Chapter 2, from which it is possible to extract the resistivity of the selected material via an equation.

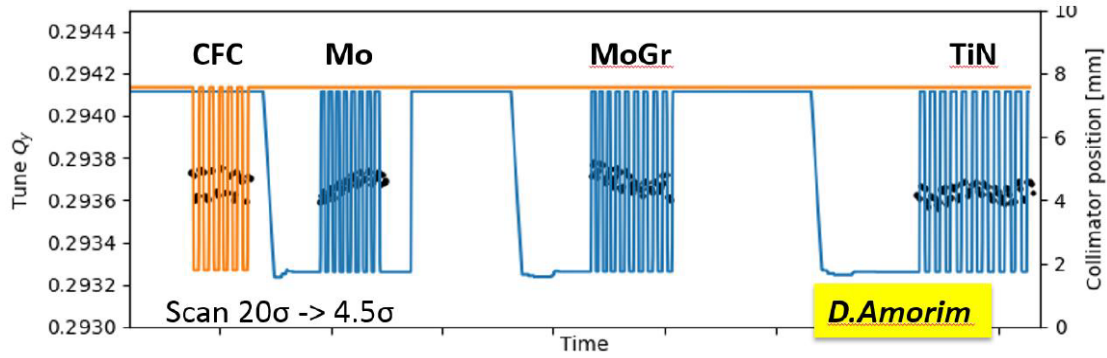


Figure 4.32. Courtesy of S. Antipov

The two different jaws positions selected for the tune shift session were 20 sigma and 4.5 sigma. The half-gap aperture is reported on the right in millimeters. The plot is showing all the points obtained with the kicking technique: each single point has been generated by kicking the bunch with the damper (ADT) for different jaws apertures. What can be seen is that in the case of Mo the difference in tune shift is smaller if compared with the one obtained for MoGr: the conductivity of the latter is in fact smaller than the Mo one. The session was also extended to the determination of the tune shift contribution given by the TCSG collimator, whose jaws are made of CFC: this material is in fact more resistive, showing in the plot 4.32 a big tune shift delta between 20 collimation sigma and 4 sigma.

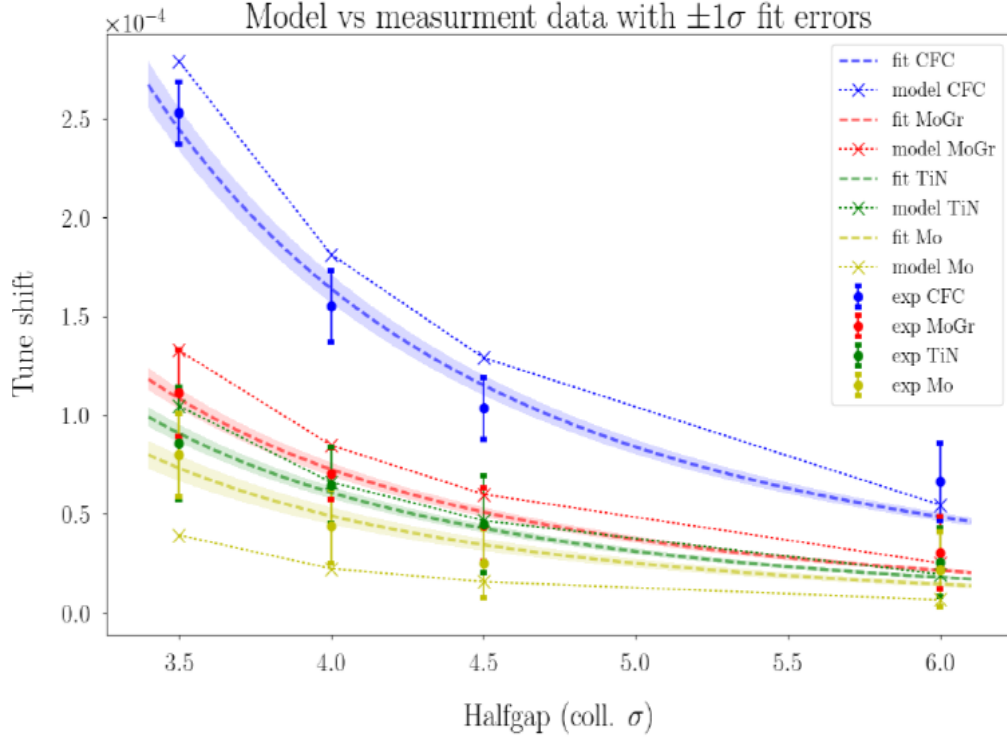


Figure 4.33. Courtesy of S. Antipov

The plot is showing the three points obtained for the three different bunches with different intensities. The little geometrical figures represent the measurements done for three different intensities, with the lines indicating the acceptable tolerance. The fitted lines represent the values predicted with simulations performed with IW2D. In the grey "after loss" column the results aren't taken into consideration because of the intensity loss that happened during the session, which is something that can significantly compromise the accuracy of the results. There is good agreement between reality and theory, the behaviour of the fit performed on the measurements and the one done with IW2D is closer. The scaling with the inverse of the square root of the resistivity is also evident, every curve is showing a different resistivity value. The only material which is having a different behaviour with respect to what was expected is the Mo, which is giving quite a higher contribution to the tune shift: this will lead to an higher resistivity value than expected.

From these results it is possible to extract the resistivities:

Table 4.2. MD measured resistivities

MoGr	TiN	Mo
760 nOhm*m	340 nOhm*m	250 nOhm*m

The tolerance for this value is expected to be around 50 nOhm*m. Comparing with the lab measurements:

Table 4.3. RF measured resistivities

MoGr	TiN	Mo
800-1200 nOhm*m	100-500 nOhm*m	20-100 nOhm*m

Table 4.4. Datasheet DC resistivities

MoGr	TiN	Mo
1000 nOhm*m	400 nOhm.m	53 nOhm.m

The values obtained show that RF and beam type of measurements are giving a really close value of MoGr resistivity, which is in its turn comparable to what expected from datasheet's values. The Mo's resistivity value obtained from RF sessions is matching the value given by the datasheet, but a noticeable difference (almost factor five) is present in the resistivity given by the beam measurements. The TiN it is almost represented by the same value in beam and datasheet tabs, but it hasn't been possible to determine its resistivity during RF measurements session.

4.3 Analysis of lateral fingers failing scenario

In the latest TCSPM design different sets of RF fingers were installed in order to grant electrical continuity to the imaginary charges moving along the structure while following the particle beam passing trough. In this specific design, which represents the one that will be installed in HL-LHC, different holes up and down (4.34) in the tank are still present and they could likely be a significant source of field leaks, producing heating and power losses in the beam's surroundings.

In order to prevent these issues in the structure two main groups of RF fingers are present (Ref.[7])

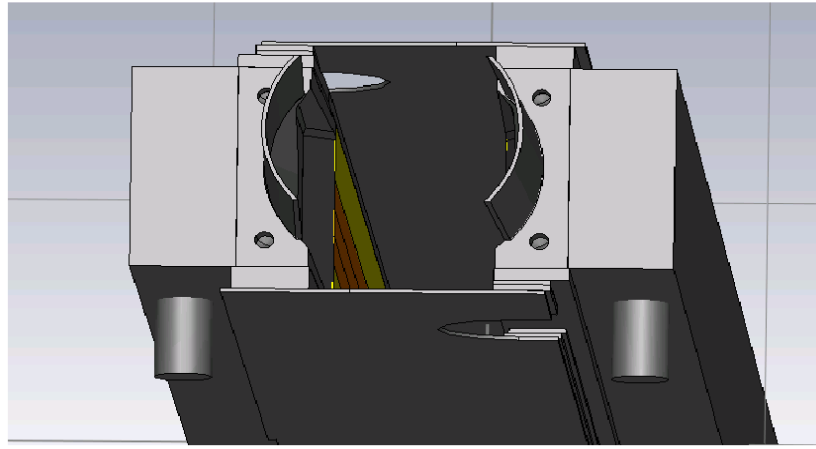


Figure 4.34. TCSPM from the front

- Longitudinal fingers, which starts from the tapers at the very beginning of the collimator and which put in contact the tapers in (4.34) with the tank itself
- Lateral fingers, as shown in picture (4.35), which totally close the holes present in the structure due to mechanical supports installation

All the models were imported again from CERN archive with SmartTeam and they have been edited and simulated with CST.

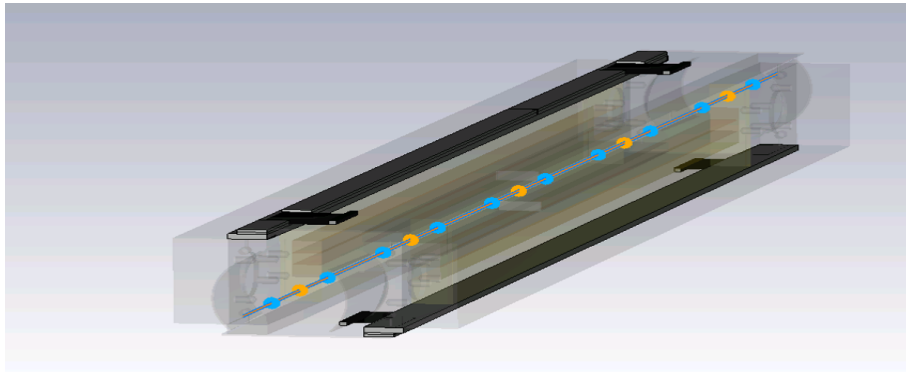
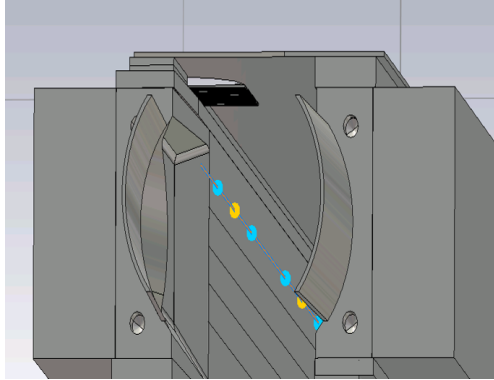


Figure 4.35. TCSPM's lateral fingers

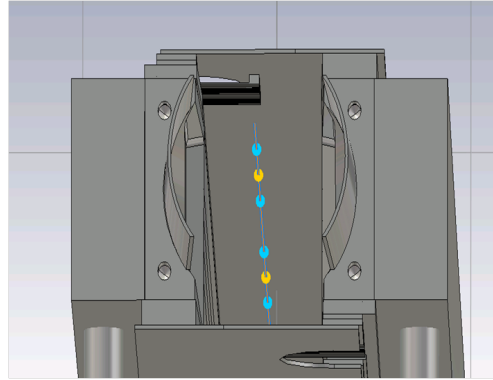
In order to better understand the impact of the lateral RF fingers four different cases were simulated:

- RF fingers not touching the structure
- RF fingers perfectly in contact with the structure
- No RF fingers

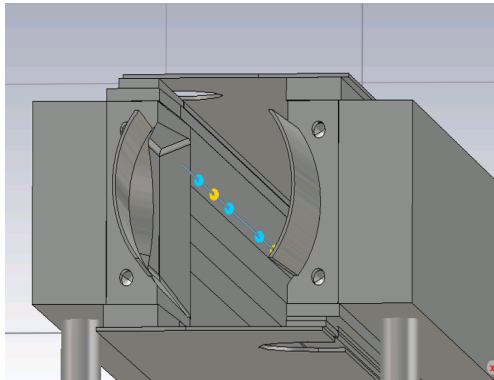
as shown in the following pictures:



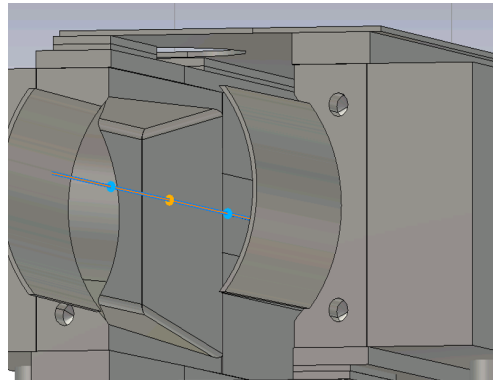
(a) No Contact Fingers



(b) No Fingers



(a) No Contact Fingers



(b) No Fingers

Even if it seems that the scenarios (a) and (b) are quite similar from a macroscopic point of view in fact they could be quite different from each other, the touching part is able to manage to prevent dispersive field effect connected to field propagation in free space: once the fingers are disconnected it could happen that they start to act as an antenna, unleashing travelling wave inside the collimator.

A preliminary analysis was performed with the structure made just of Perfect Electric Conductor(PEC) as to identify the principle resonant modes contributing to the geometrical impedance, with this kind of material there's absence of damping effects which make easier to detect where the modes are located in frequency. Following the preliminary results obtained:

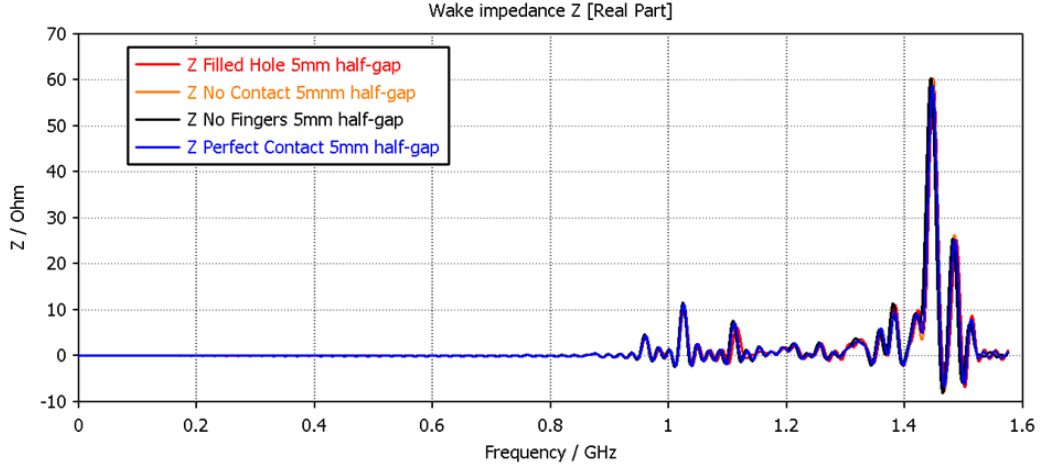


Figure 4.38. Longitudinal Impedance, Real part

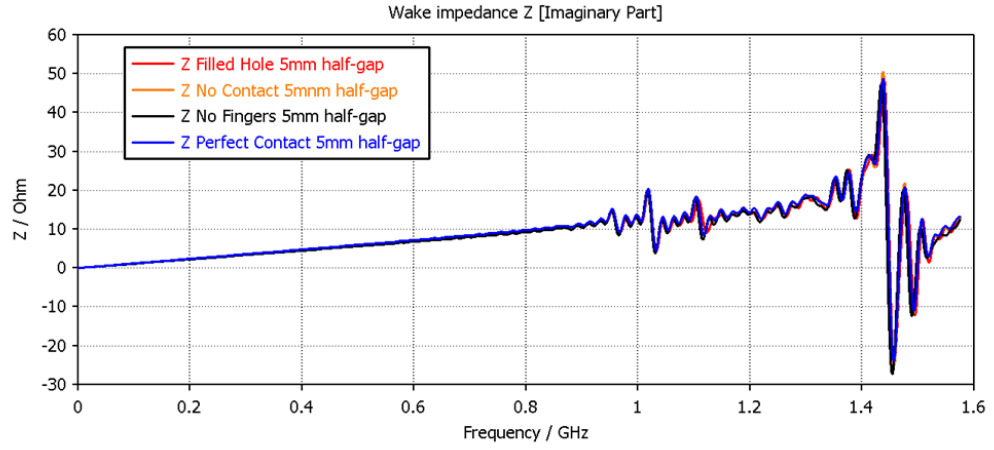


Figure 4.39. Longitudinal Impedance, Imaginary part

In the plot is shown the real part of the longitudinal impedance as a function of frequency for different half-gaps in all the previous four scenarios. Obviously to achieve the most accurate impedance functions many half-gaps should have been simulated, with a step of 0.5 or 1 millimeter. The span of half-gaps simulated have been chosen as to cover the possible aperture scenarios: these three values (5mm, 20mm, 30mm) are a good compromise between the number of simulations (each aperture requires many) and the expected possible behaviours which could happen in reality. From plots 4.38 4.41 it is shown how with 5mm half-aperture. The impact of fingers is almost negligible, all the four possible scenarios are showing almost the same impedance function both in real and imaginary part (same Z/n). In figures 4.40 4.41 the same behaviour appears on the real part of the impedance, not many effect are detectable from the functions behaviour. The noticeable difference is present in the imaginary part where the Z/n is experiencing a slight change by varying of a few Ohm between the scenario without RF Fingers and the other three.

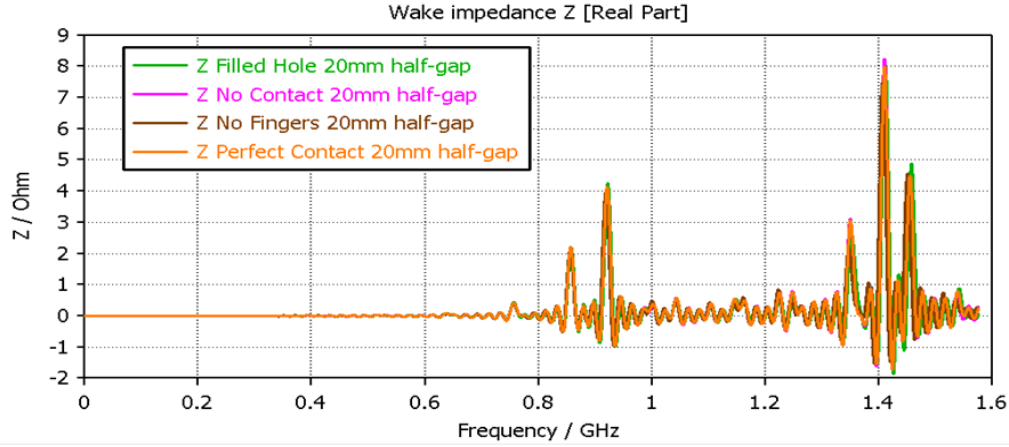


Figure 4.40. Longitudinal Impedance, Real part

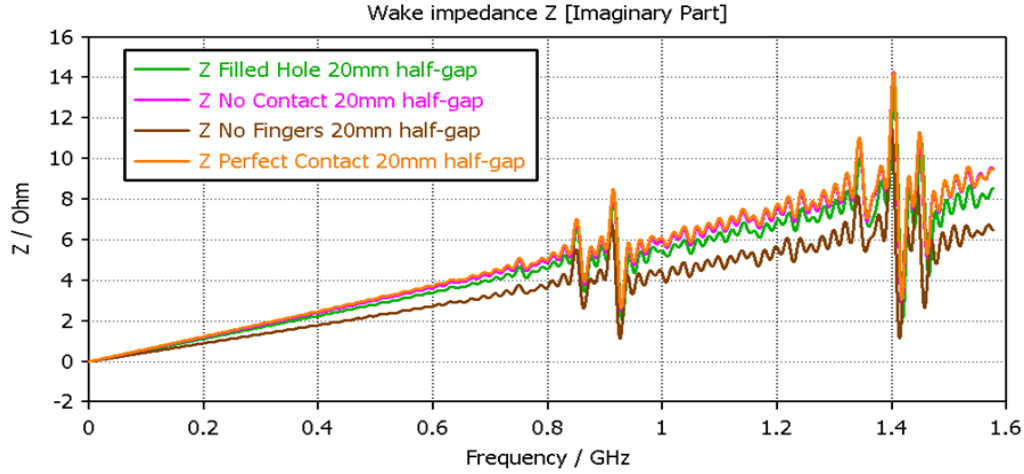


Figure 4.41. Longitudinal Impedance, Imaginary part

The impact of not touching fingers can be clearly seen in plot 4.42–4.43, in brown line: below 1.2 GHz basically the modes are the same for all the configurations, above that frequency a big change in longitudinal impedance can be clearly detected, there is one order of magnitude between the resonant modes which belong to no-contact fingers scenario and the ones which belong to the other three configurations. To be noticed that there is no resistive wall contribution in all the plots due to the fact that PEC has an infinite conductivity, which leads to a broadband contribution which is zero everywhere in all the frequency range, without any dependence on the half-gap value.

From this preliminary analysis the outcome is that there's a clear contribution of contactless fingers starting from 30mm half-gap, which is linked to the fact that the jaws are partially shielding the lateral apertures (holes up and down) for a certain span of half-gaps.

The analysis will continue now in order to further analyze the most dangerous scenarios shown in pictures 4.40 4.41 4.42. 4.43.

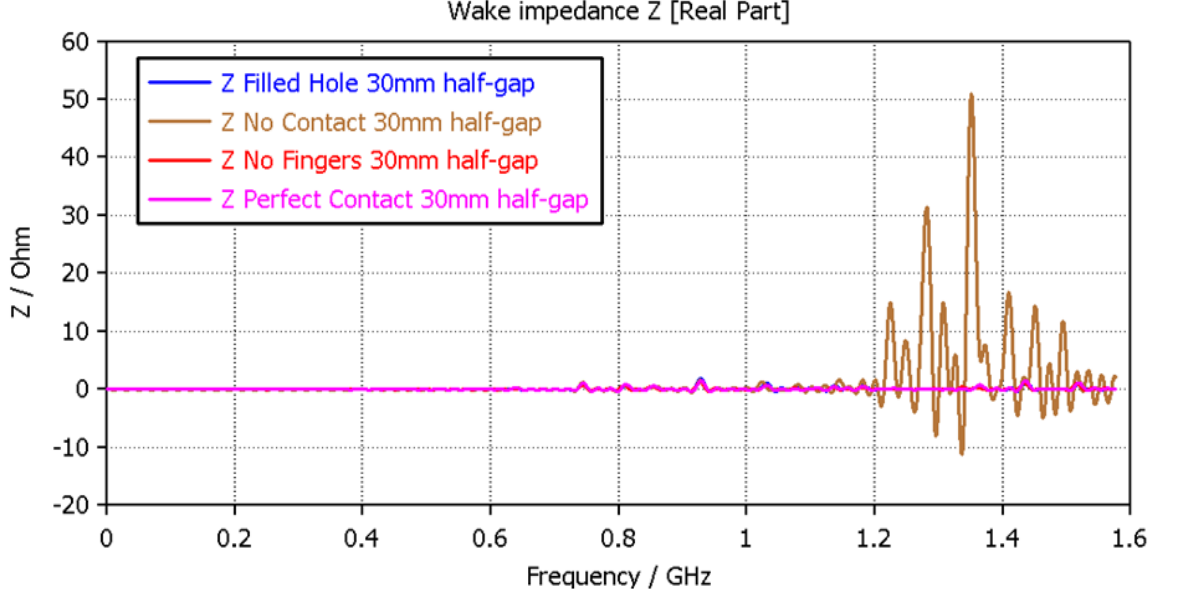


Figure 4.42. Longitudinal Impedance, Real part

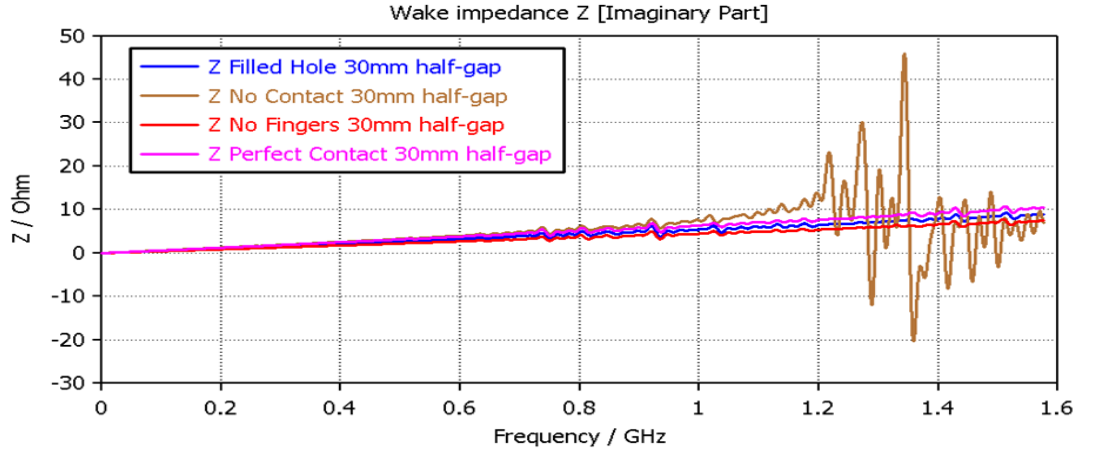


Figure 4.43. Longitudinal Impedance, Imaginary part

The configuration with half-gap 20mm in the previous set of simulations was presenting different Z/n values for different cases, from picture 4.41 it is shown how the absence of fingers was decreasing the broadband contribution of the imaginary part. To further investigate these results the real model with all the real materials was used together with an increased wavelenght: this could lead to different values of Z/n , which is linked to the fact that with a longer integration window (wavelength) a more reliable discrete fourier trasform is achievable, increasing the accuracy of the results.

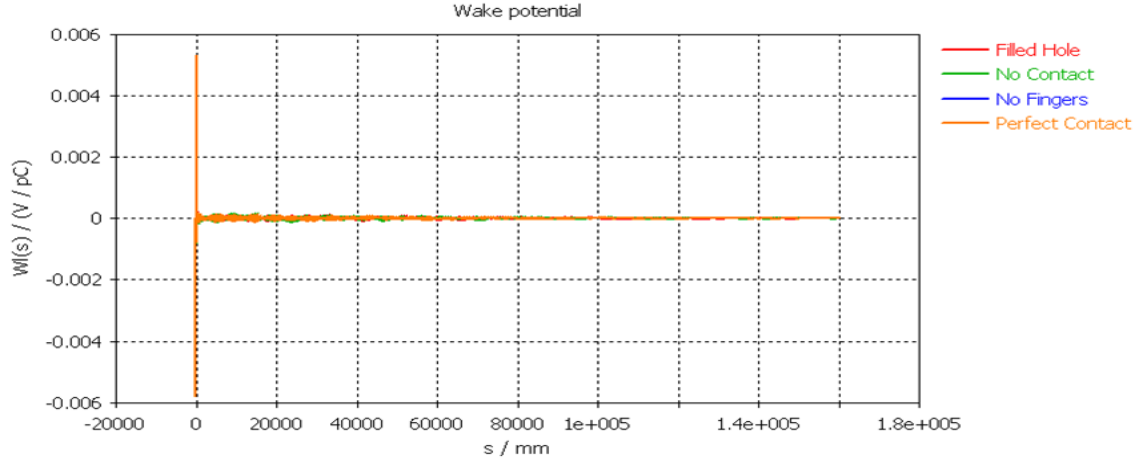
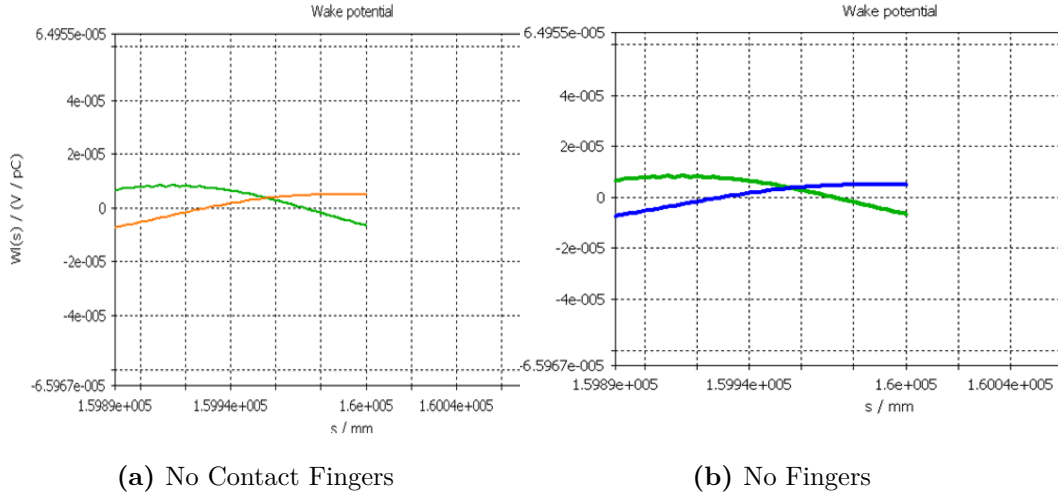


Figure 4.44. Wake potential

In picture 4.44 the wakefield obtained for the four different scenarios is shown with a length of 160 meters. Not many differences could be noticed from the four different behaviours, the resonances are experiencing the same time decaying with similar patterns.



The wakefields shown are almost totally decayed after 160m, this will significantly increase the quality of the Fourier transformations.

In the new evaluated impedances many differences are now noticeable, the broadband contribution of the real part is now something clearly detectable, all the modes are now laying on a slowly-increasing baseline in all the span of frequencies. Another detectable effect is the slight mode-shifting visible in the 4 overlapped behaviours, feature that could be also been assigned to the precision of the impedance functions evaluated by CST.

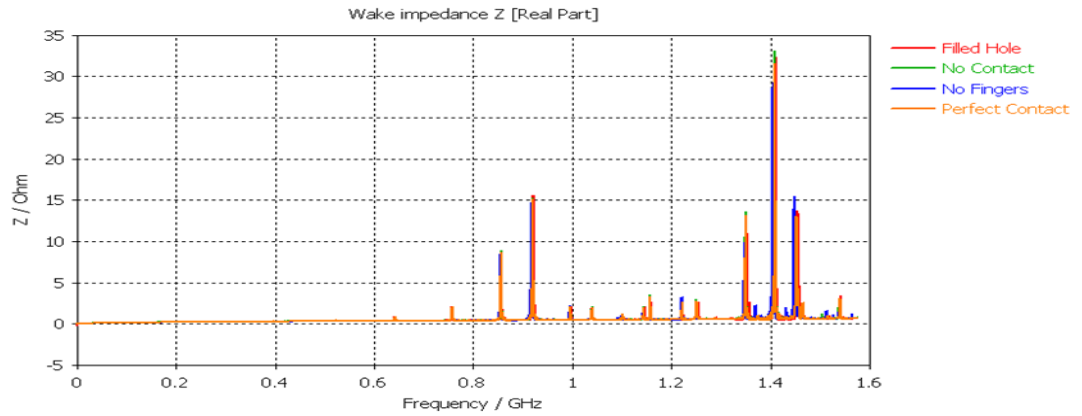


Figure 4.46. Longitudinal impedance for 20mm halfgap, Real

The Imaginary part has now reached different and more accurate values of Z/n , leading to different results.

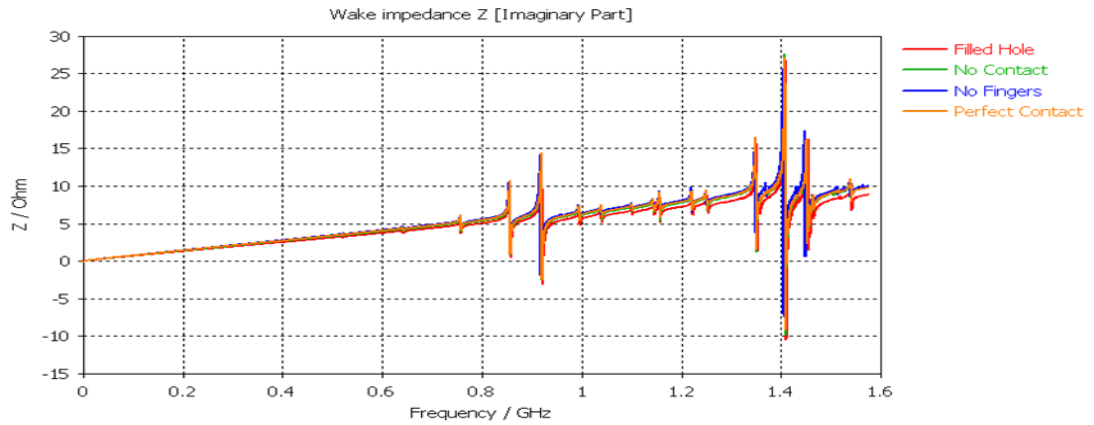


Figure 4.47. Longitudinal impedance for 20mm halfgap, Imaginary

The different broadband contributions in different scenarios are quite similar and they have small values from the point of view of single bunch effects, the impact of contactless fingers is then not an issue for beam instabilities and possible related effects.

	Filled Hole	No Contact	No Fingers	Perfect Contact
Z/n	0.07m Ω	0.075m Ω	0.078m Ω	0.077m Ω

Figure 4.48

In fact the Z/n is just changing of some mOhms from the smallest value given by the filled hole scenario as show in table 4.48. All this values don't seem critical if compared to the LHC estimated budget for single bunch instabilities, which is been

evaluated as approximately 90 mOhm.

The other interesting scenario produced from the simulations with the structures made of perfect electric conductor (PEC) was the one with 30mm half-gap aperture (4.42). Also in the case the simulations have been redone with real materials and a longer wake. Following wake potentials of the four scenarios:

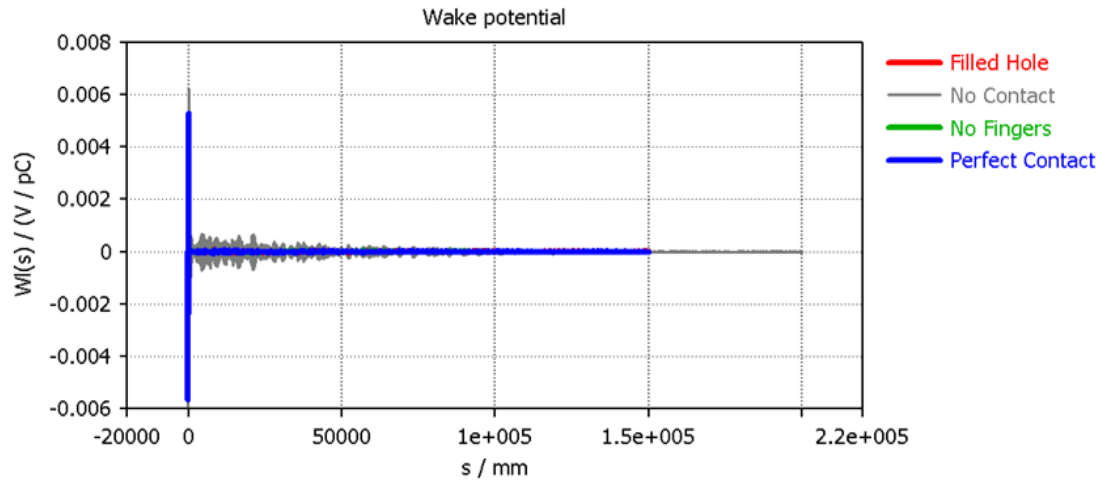


Figure 4.49

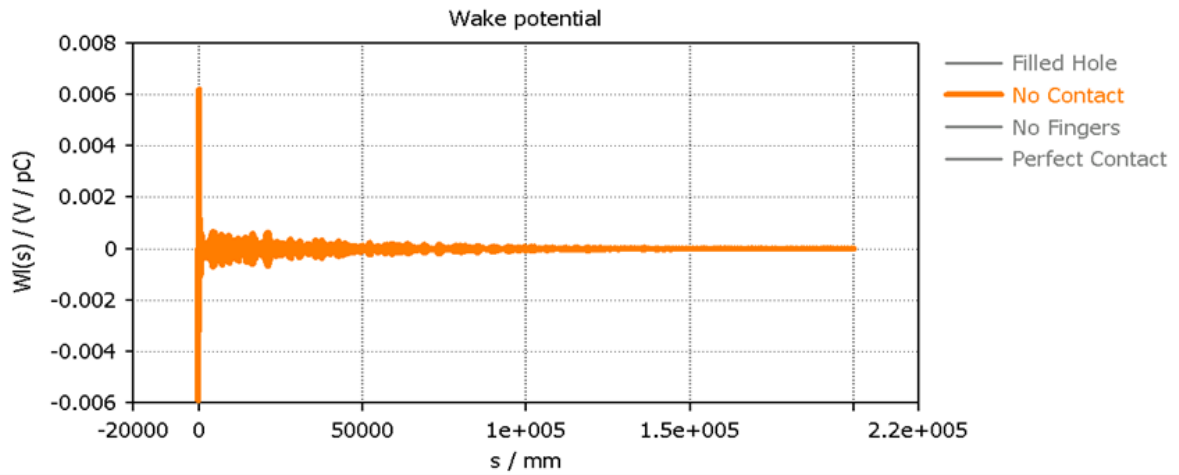


Figure 4.50

In the plots 4.50 and 4.49 the differences between the fingers not touching and the three other cases are shown. The wake potential in orange results with a stronger resonant pattern compared to the others, which implies the presence of many visible resonant modes once Fourier-transformed. The effect of the impedance coming from this ringing (it is quite a long one, it took 220m of wakelength to make it decaying) can be seen in the impedance behaviour in plots 4.51 4.52 In the real

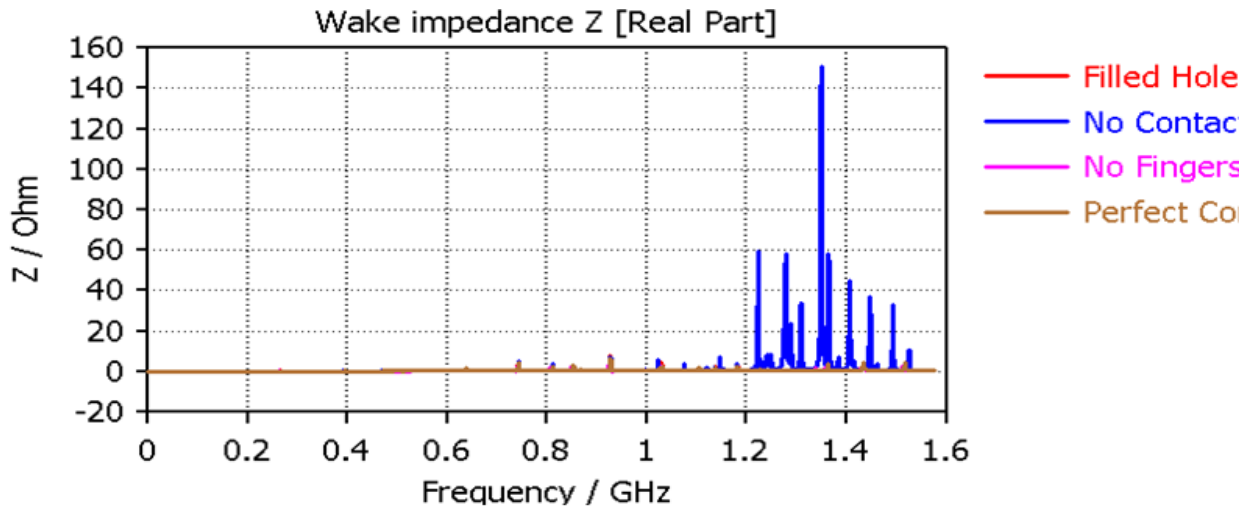


Figure 4.51

part is quite clear how the missing contact is unleashing many dangerous modes inside the structure, the order of magnitude of the function in blue is reaching really high values above 1.2 GHz compared to the others, especially around 1.36/1.37 GHz. By visual inspection it is also evident how the materials of the structure are not absorbing much energy, the presence of narrow peaks denote how the modes are not damped, which implies that most of this energy will stay inside the structure while it is resonating. This is something to be checked also with Eigen Mode simulations in frequency domain, which offer a better reliability in the determination of the quality factors.

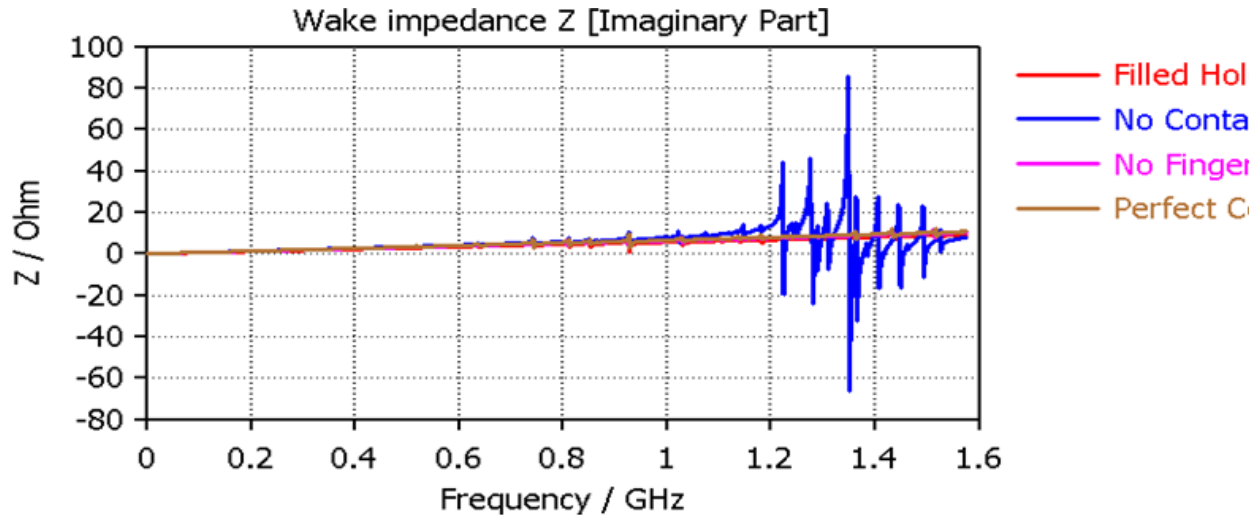


Figure 4.52

The Imaginary part is showing a slightly higher broadband part due to the higher values of R/Q now present because of the resonant modes. To be kept in mind that

this effect is related just to the longer window used in the wake potential evaluation, which leads to a more complete Fourier transform, and not to the material used, being the broadband part just dependent on the sum of Z/n values.

The 30mm half-gap scenario has proven to be the only one which is really significantly contributing to the impedance, especially in the real part.

In order to confirm that the RF fingers are actually acting as a $\lambda/4$ resonator eigen mode simulations have been also performed for the 30mm scenario. Following in plot 4.53 the match between the shunt impedances of all the modes in the structure and the wakepotential previously evaluated is shown

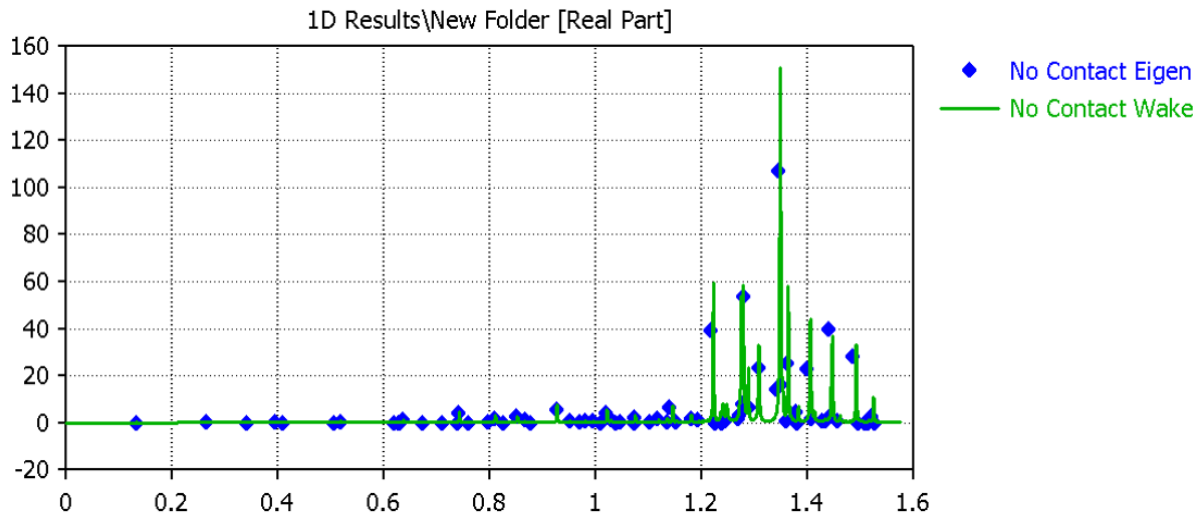
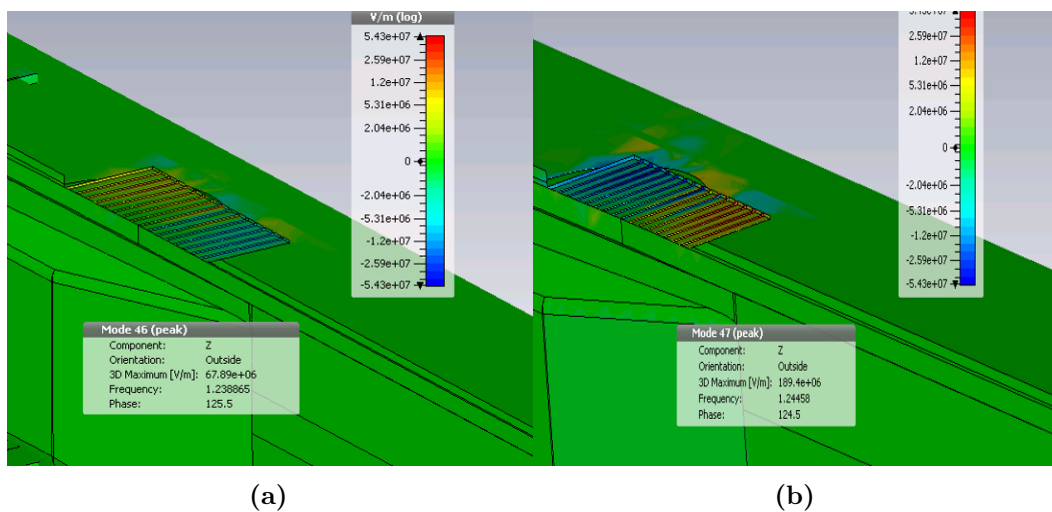


Figure 4.53. Eigenmode vs Wake impedance

The comparison between the two type of simulations shows a good agreement, confirming the good accuracy of the results. The fingers are then literally acting as an antenna, releasing electromagnetic field patterns inside the collimator tank.



In pictures 4.54a 4.54b some of the more dangerous modes evaluated from

eigenmodes simulations are shown, highlighting the sinusoidal field pattern on the RF fingers.

Eigenmode and wakefield simulations have been compared also in the scenario with perfect contact fingers, showing again a good match. Comparing then the two most realistic and possible scenarios both in Eigenmode and wake simulations it is possible to highlight the main significant differences:

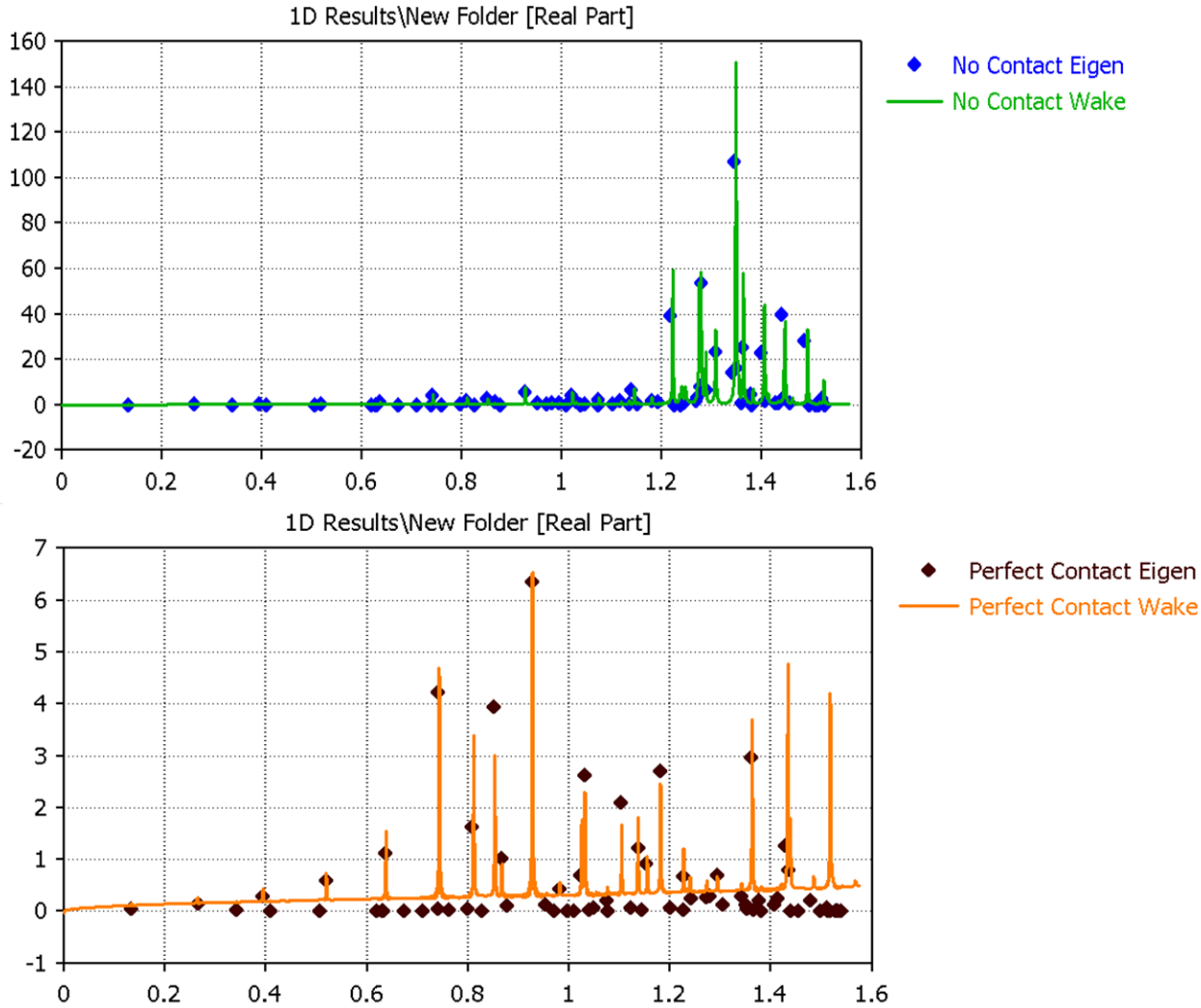


Figure 4.55

Basically by looking at the two plots there is a factor two of magnitude between the contactless scenario and the perfectly touching one, which implies that in such a device the lateral RF fingers need to touch in order to grant electrical continuity in the structure. If this doesn't happen many resonant modes will be produced by the shielding devices acting as four antennas, with its peculiar lambda quarter resonating pattern unleashing field in all the tank.

4.4 Analysis of the segmentation of the jaw's bulk blocks

The collimators are devices in which different moving parts (called jaws) made of peculiar and specific materials are moving in order to act on the beam halo, performing what it is called the beam-cleaning. These jaws could be made in several ways, leading to different impacts on impedance and beam instabilities. The two main techniques used to assemble collimator's jaws are the one in which these components are made just of a big bulk block of material and the other in which the jaws are segmented in smaller blocks. The impact of this second technique on TCSPM impedance will be investigated, in order to assess the different contributions to impedance given by the segmented blocks and the bulk one. In TCSPM collimator project the jaw will be made of 6 different blocks put into contact in order to build a big bulk one. During the bakeout it could happen that they start to separate a bit between each other, forming 7 gaps of 0.1mm in the jaws, as follows (Ref.[8]):

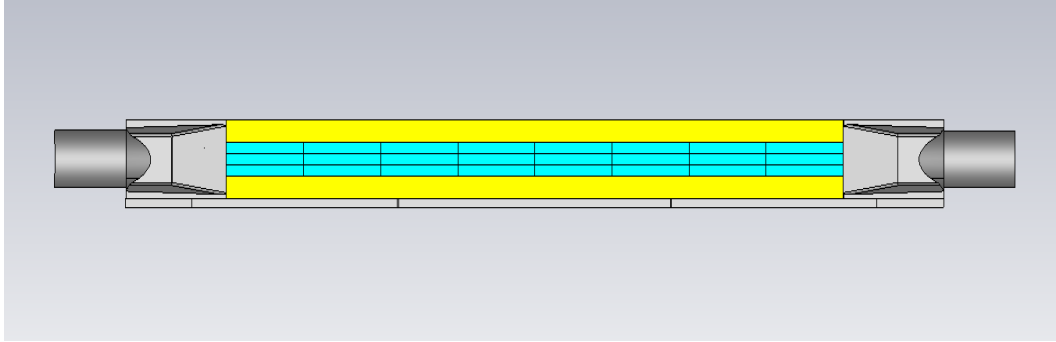


Figure 4.56. segmented jaws, section

Each stripe of material is then separated in different parts, leaving a little space in which the electromagnetic field produced in the space by the travelling bunch could be remain trapped, generating resonant modes mostly below the cut-off frequency itself of the pipe.

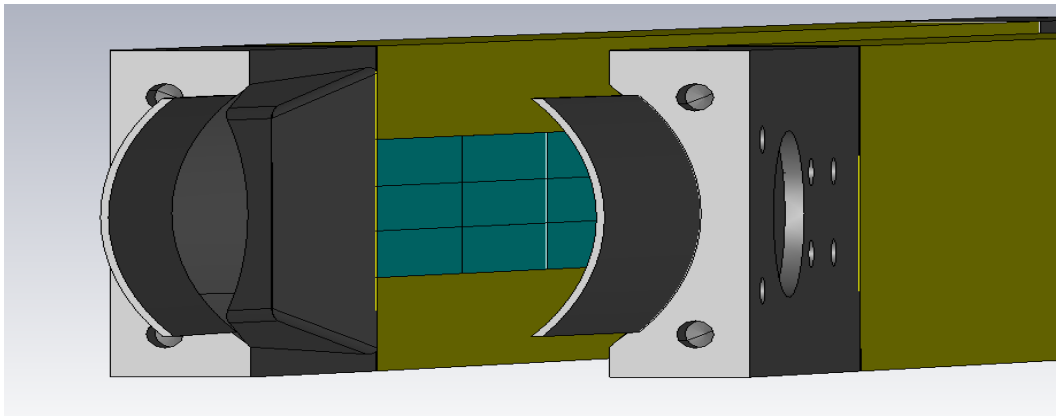


Figure 4.57. segmented jaws, front

In this new configuration the impact of the blocks segmentation on longitudinal impedance is strongly dependent on the half-gap aperture values. In order to keep this

into account different scenarios for different half-gaps were simulated: the smaller is the distance between the jaws and the bigger should be the impact given by the resonant modes created by these spaces on the coupling impedance. Following the results obtained with CST:

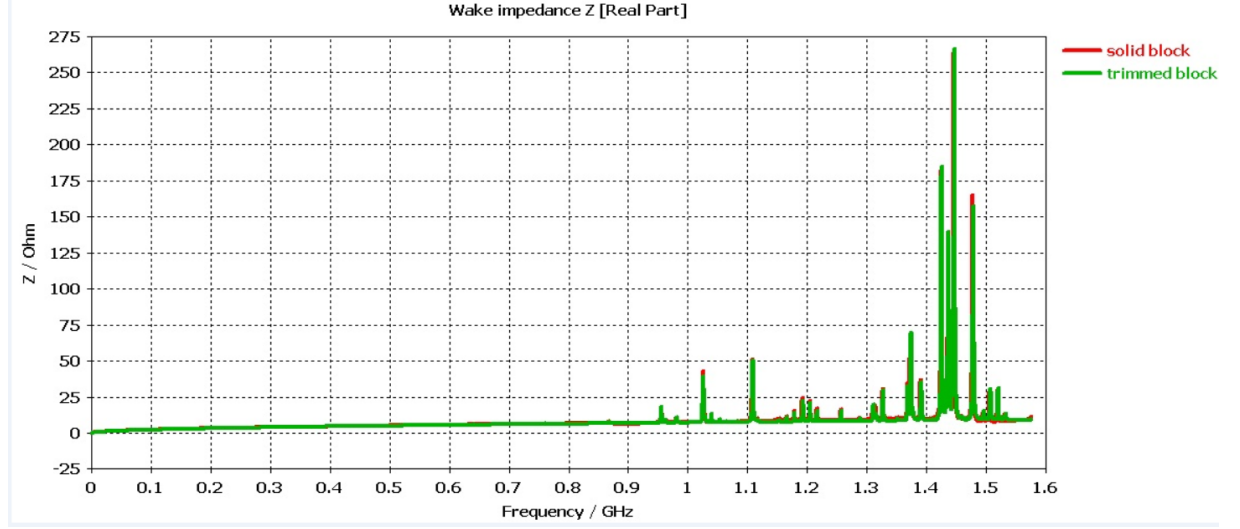


Figure 4.58. 1.5mm half-gap

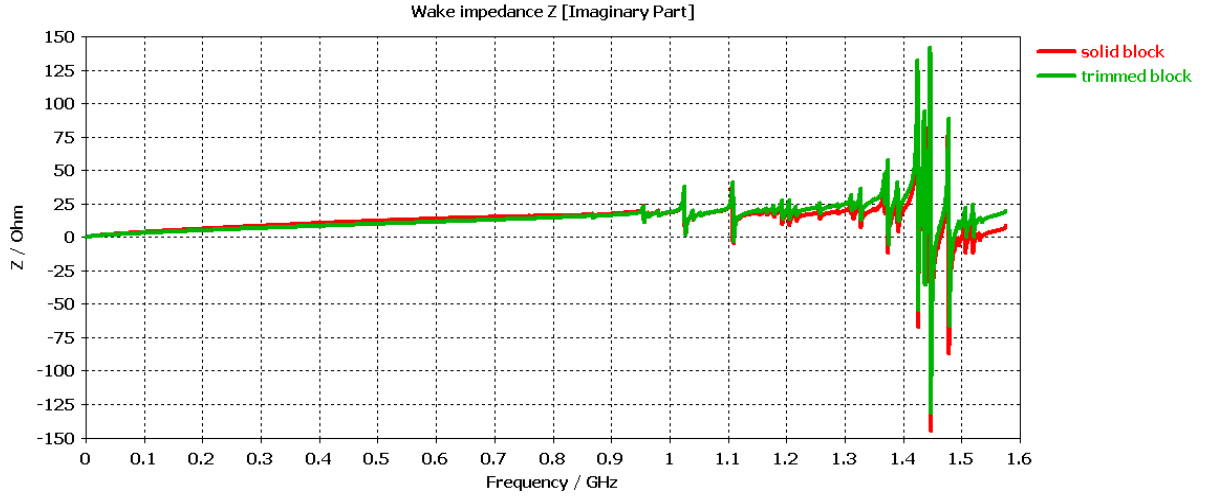


Figure 4.59. 1.5mm half-gap

This scenario represents what it was expected to be the most dangerous jaws configuration possible: 1.5mm half-gap aperture is in fact the tightest aperture available for the TCSPM collimator. From the plots there are no significant differences between the solid block scenario and the trimmed block one, the results obtained show similar impedance functions.

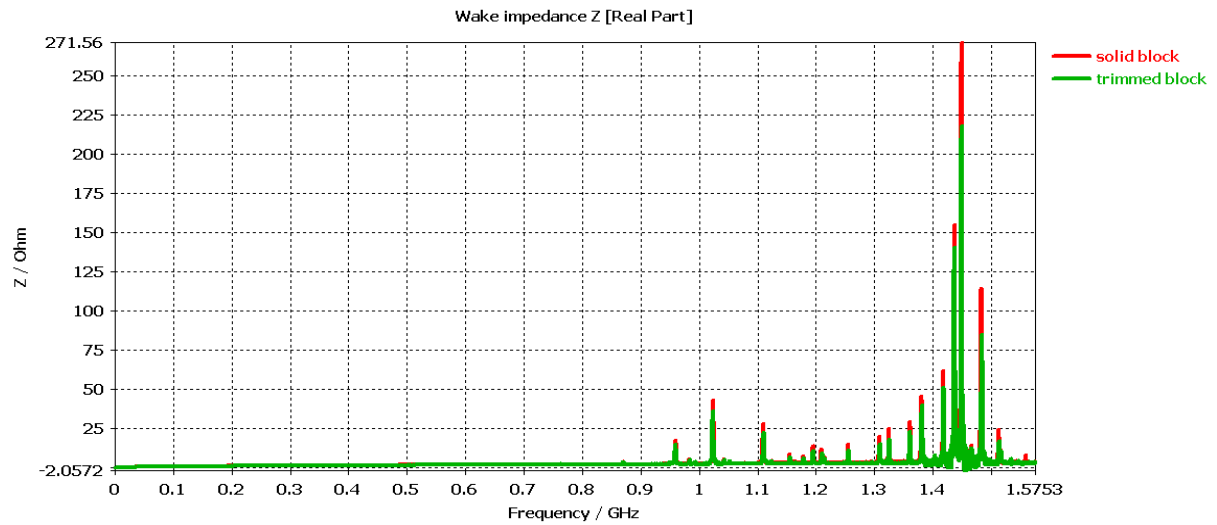


Figure 4.60. 5mm half-gap

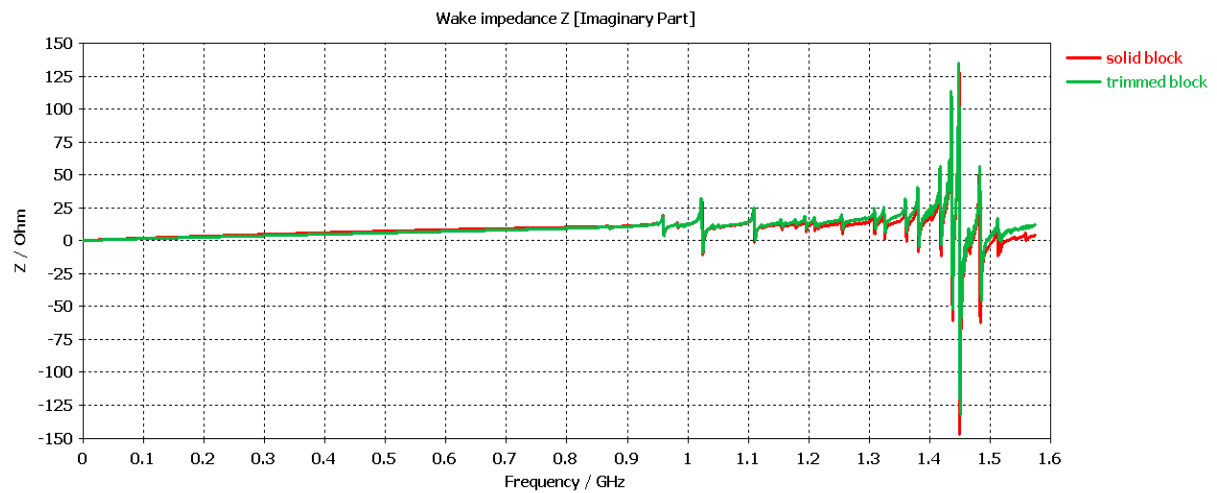


Figure 4.61. 5mm half-gap

Also with 5mm half-gap aperture the differences are not much important if all the frequency span is considered. Something that can be noticed is the presence of amplitude's decreasing in the real part of the longitudinal impedance in the case in which the block forming a single jaw is trimmed, especially between 1.4 and 1.55 GHz, where the narrow contribution given by the resonant modes is visibly smaller. In these simulations the wake potential has been brought to convergence, the peaks are likely representing the shunt impedance of a given mode at the same frequency, it is possible then to consider the values of the amplitudes as reliable.

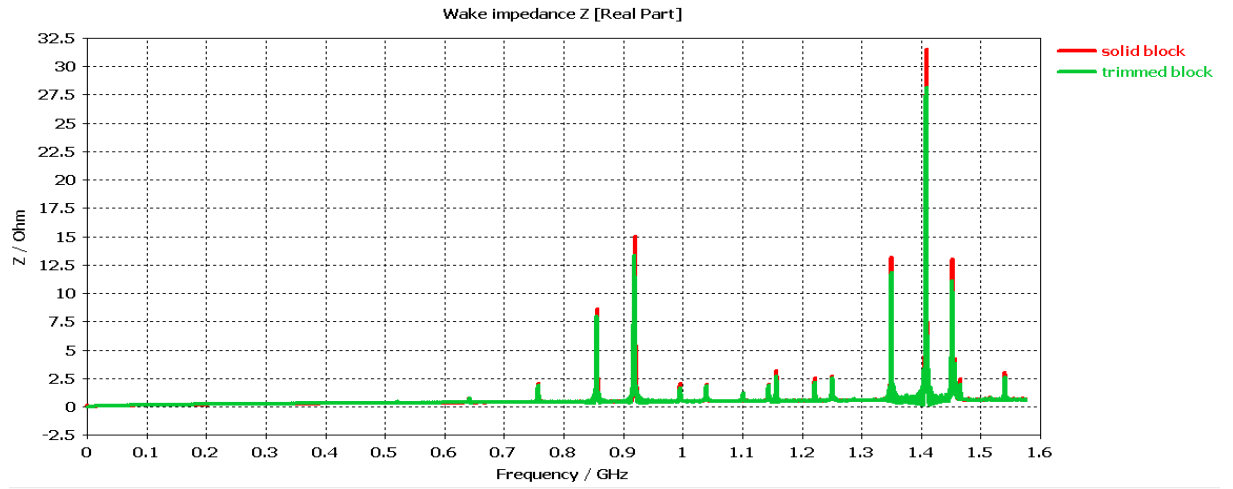


Figure 4.62. 20mm half-gap

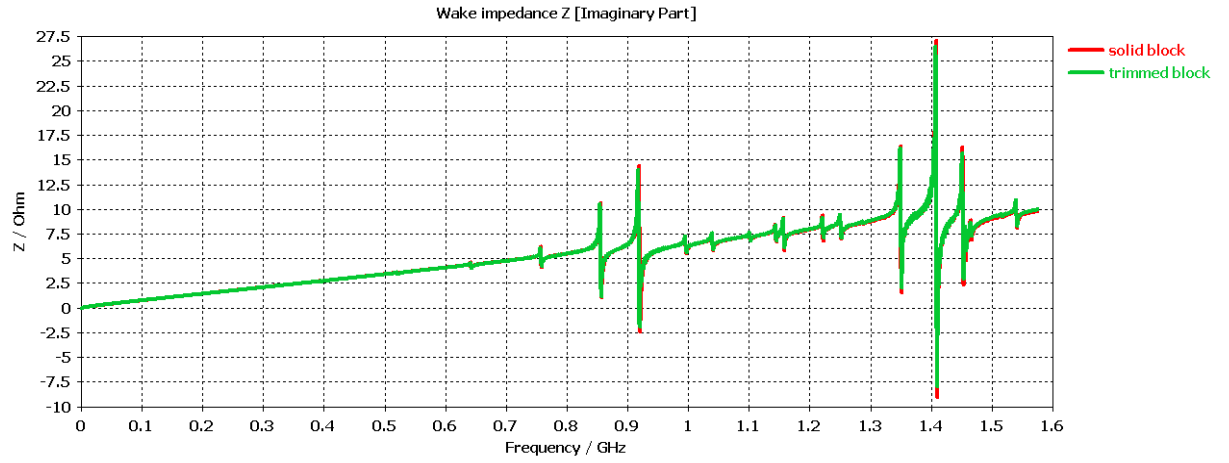


Figure 4.63. 20mm half-gap

The same behaviour is present in the 20mm half-gap aperture scenario, the amplitude of the peaks when the block is trimmed is decreasing a bit: considering the values this doesn't represent a big change, the delta is around 2.5/3 Ohm per resonant mode.

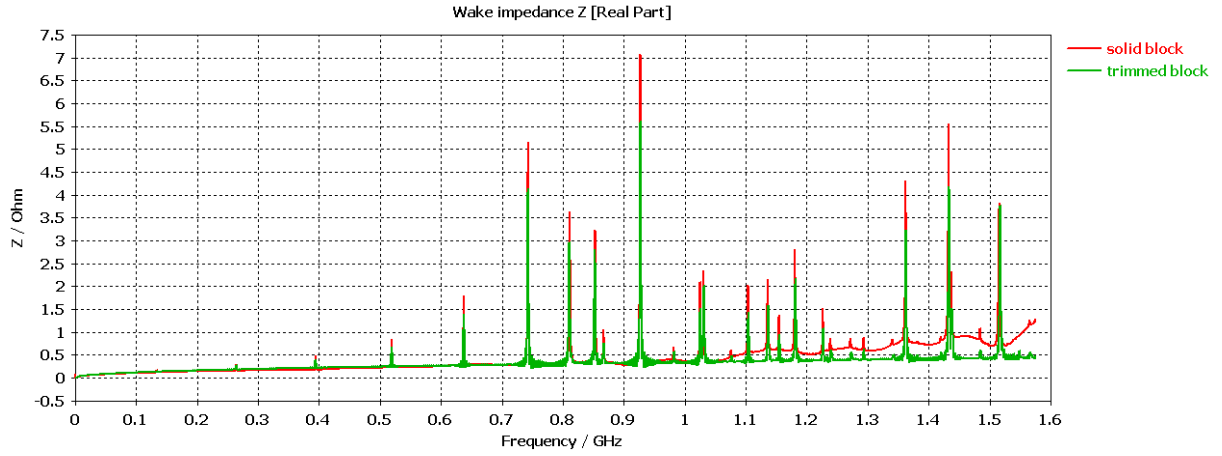


Figure 4.64. 30mm half-gap

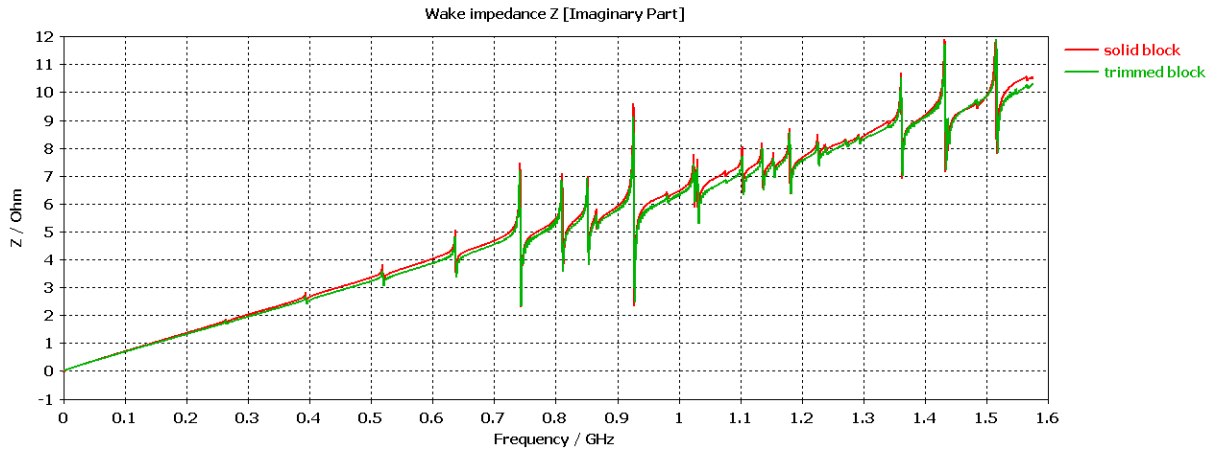


Figure 4.65. 30mm half-gap

In this analysis the expectations were to find different contributions to the longitudinal impedance for different half-gap aperture values: with the gap decreasing a larger coupling impedance should have been found in the study of the structure. What was discovered instead is that with a spacing of 0.1mm between the small blocks composing a bulk jaw the impact on impedance is almost negligible, for different aperture it is not possible to notice significant differences. These small spaces are present in the structure just in the worst constructing scenario possible, the one in which after the bake-out the blocks are not coming back to their original positions: usually there is no space left between those, the small blocks are stuck together to form a new big one. In the light of this fact it is possible to conclude that there's no potential danger in the fabrication process for the TCSPM from the coupling impedance point of view.

Chapter 5

TDIS coupling impedance analysis

5.1 Overview

The Large Hadron Collider is composed by eight arcs and eight straight sections. Each section has a fundamental function in the machine and it is performing a very specific action without which accelerating protons won't be possible. The tasks are beam cleaning, beam dumping, injection and collision. The Injection Protection Target Dump (TDI) is a device located in the two LHC points where the injections from the SPS take place: its purpose is to protect the LHC and its components in case of missing kicks on injected beam or in case of asynchronous kicker firing when the beam is already circulating (Ref.[1]).

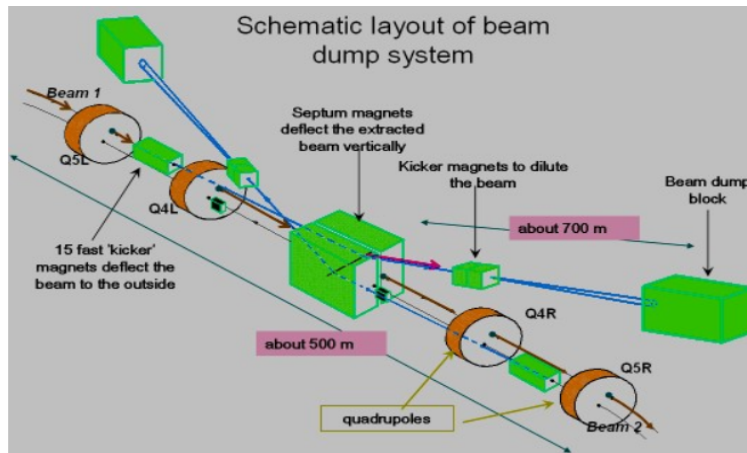


Figure 5.1. Courtesy of CERN

It is important not to confuse the TDIs with the beam dumping system present in LHC, which has a different structure and function. The LHC beam dumping system has in fact been designed to make a fast extraction of the two circulating beams from each pipe of the accelerator with the minimal amount of losses. The particles are then transported to an external dump blocks, which are located in

caverns at the end of a 700 m long vacuum line.

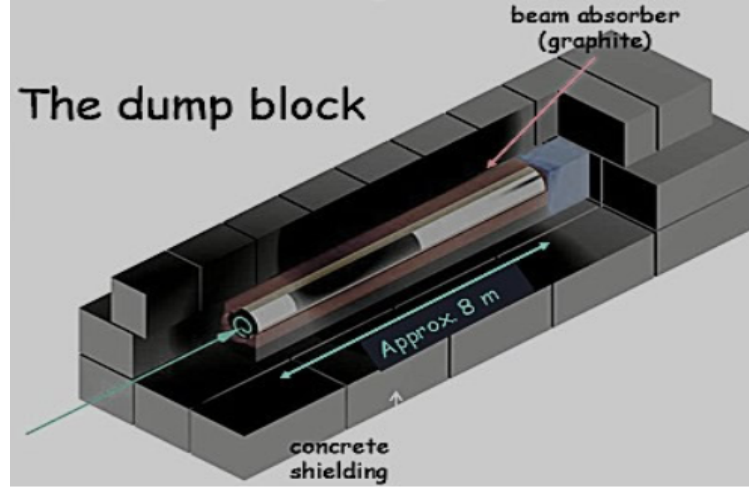


Figure 5.2. Courtesy of S. Redaelli

These blocks are long 8m and they are made of graphite and concrete. The absorbing part is the graphite, which is a material with good absorbing capabilities: using a light, high-melting-point material like graphite ensures that the beam energy is distributed throughout the block, and that the block will last for the decades-long life of the LHC. The TDIs foreseen for HL-LHC has a lot in common with the dumping system but, as mentioned before, it has a different function and it is made in a very different way: it is composed by three different tanks each one with a pair of moving jaws. These jaws are using the same technology present in the dump block: they are fully made of graphite in order to be able to withstand a direct impact with the beam at flat top in case of kicker failing, as shown below [13]:

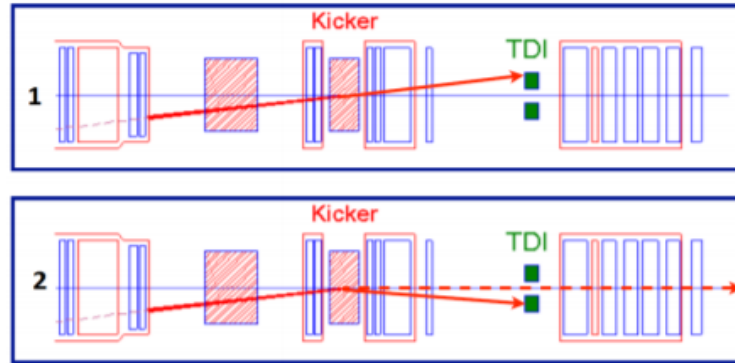


Figure 5.3. Courtesy of S. Redaelli

In this chapter the upgrade of this device will be discussed and a coupling impedance study will be performed in order to understand how the latest structural upgrades are changing the electromagnetic properties of the structure in the scenario in which a beam is circulating through the device.

5.2 From TDIS 1.0 to TDIS 2.0

The original model of the TDIs 1.0 has been recently updated to a new version, the TDIs 2.0. This device is now presenting some important differences in the geometry of its internal components, especially on the part which is directly in contact with the beam itself.

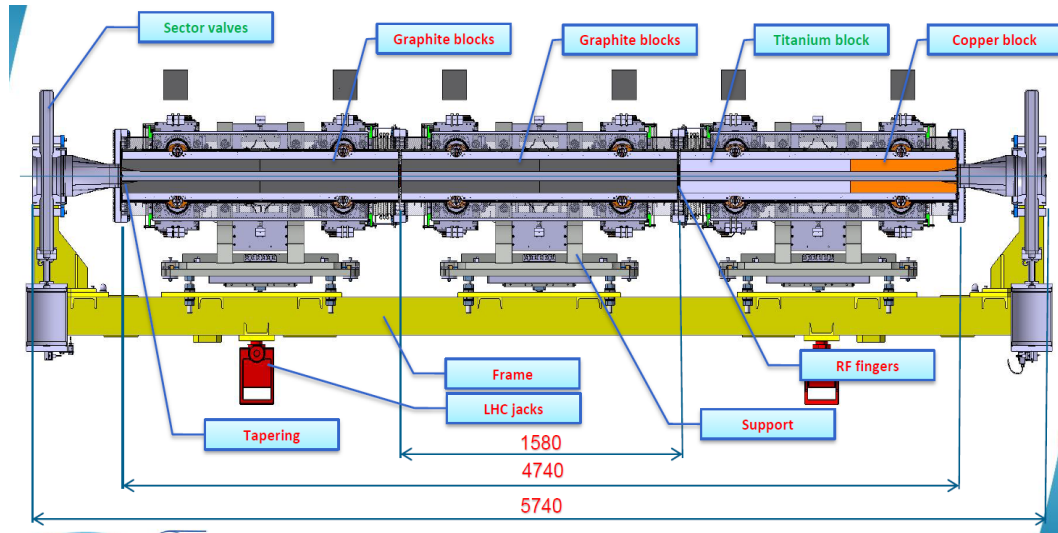


Figure 5.4. Courtesy of L. Gentini

Its jaws have been redesigned with new geometrical dimensions in order (Ref.[5]):

- To allow for more space for the insertion of the jaws into the tank
- To make the back stiffener narrower: now it is made out of TZM instead of aluminum (for strength reasons), which makes it much more expensive and also (due to the higher density) much heavier. By reducing the width of the stiffener it is also possible to save quite some weight and cost.

In picture 5.4 the new layout of the TDIs is shown: in green are indicated the changed components while in red the not changed ones. The sector valves are not something that can in any way have an impact under the impedance point of view while the titanium block in the last tank is likely to give a contribution to the coupling impedance: the material is not copper anymore, the titanium has a worse conductivity, which implies a different resistive wall contribution to coupling impedance.

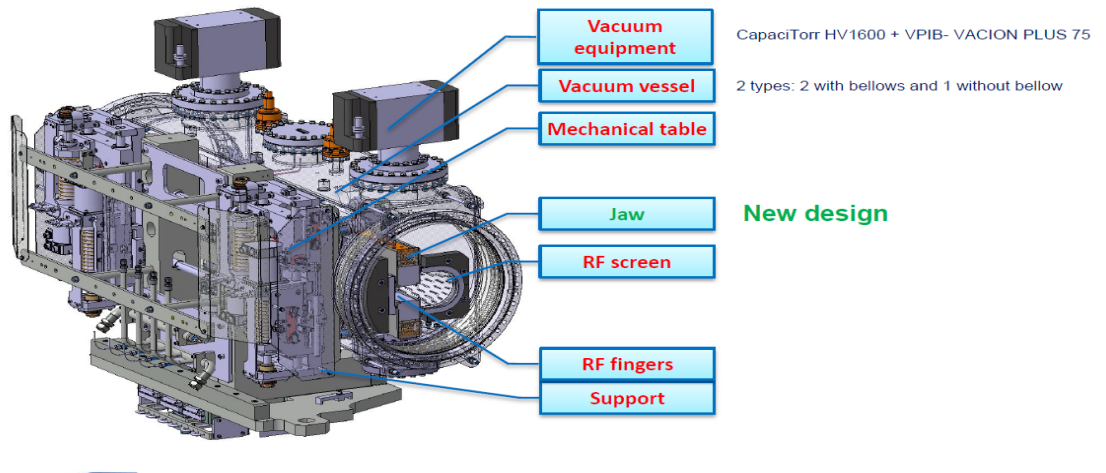
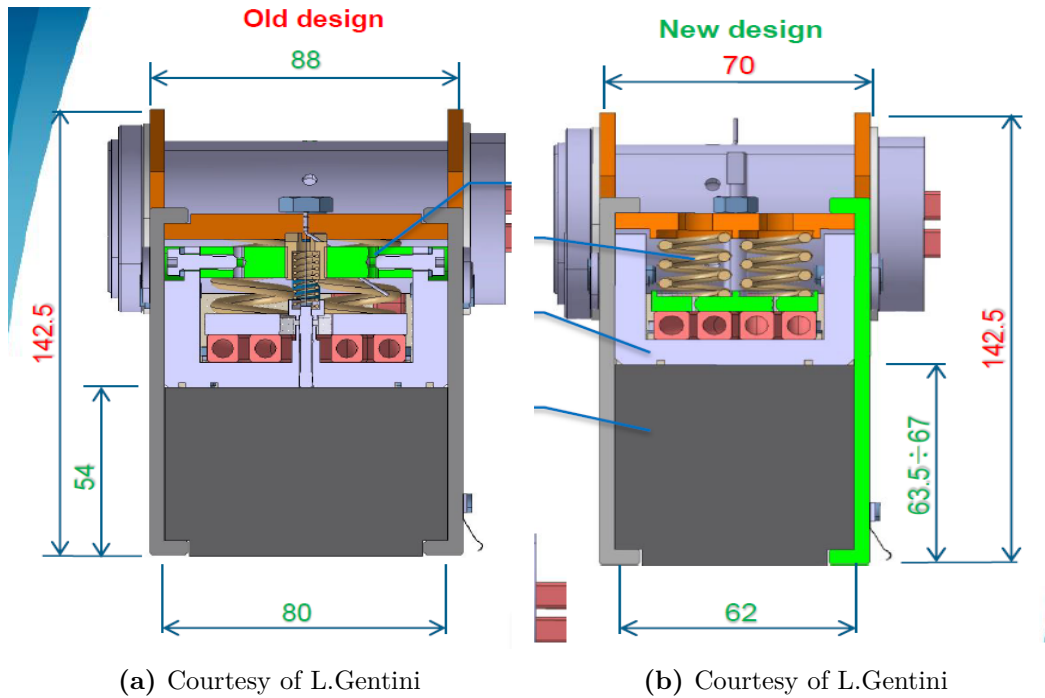


Figure 5.5. Tank detail (courtesy of L. Gentini)

By taking a closer look to the tank itself it is clear how the geometry of it hasn't been changed much: the only things that have been experienced some modifications are the jaws.



In the new design the blocks inserted into the jaws have significantly changed dimensions: the width is now 62mm and the height is between 63.5mm and 67mm (the definitive value has been recently chosen to be 67mm, the one assumed for simulations is 65mm). These changes can strongly affect the coupling impedance: the new geometry could be in fact responsible for the presence of many new resonant

modes inside the structure, which is something that needs to be investigated. The resistive wall impact coming from these modifications should be almost the same as before, considering that the width of the material directly interacting with the beam is not able to change much the quantity of image currents flowing in the blocks of conductive materials. A new model has been then imported from Cern repository via SmarTeam and converted into a CST file:

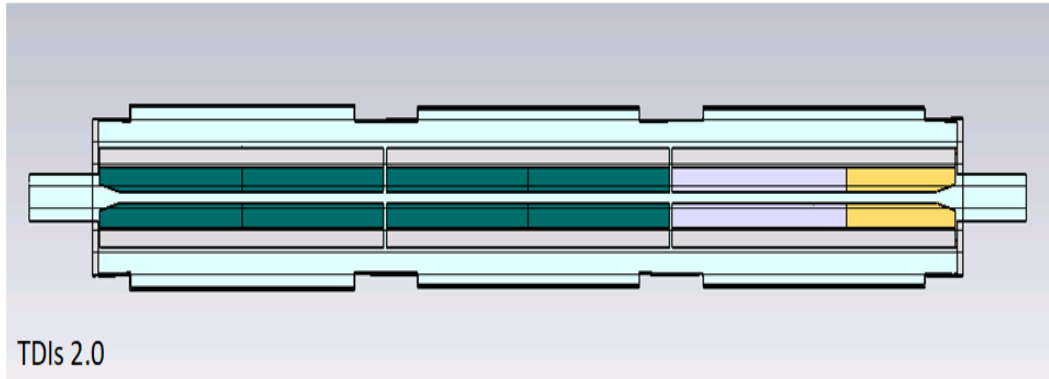


Figure 5.7. TDIS model side view

All the original features and dimensions were preserved in order to have a good reliability in the simulated structure, as shown.

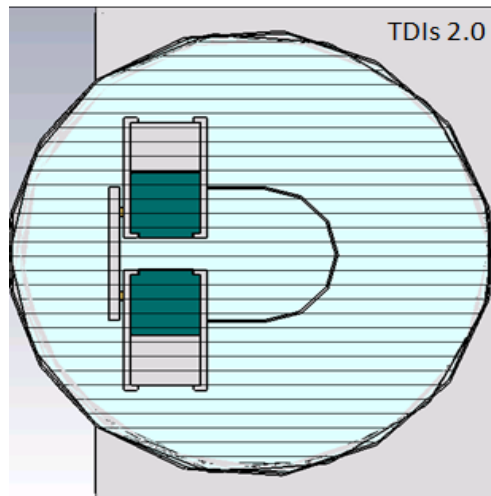


Figure 5.8. TDIS model front view

Apart from evaluating the coupling impedance of the TDIs 2.0 the main target of this experimental analysis is to simulate and comprehend what kind of impact can be given by the spaces between different tanks, and consequently different jaws and blocks. In the model now there are longitudinal RF fingers which grant electrical continuity between the different blocks, but in this type of structures quite often the mandatory perfect contact of fingers could happen to fail, leading to many resonant modes mainly focused in the region in which the shielding is not effective anymore.

5.3 Longitudinal Impedance comparison between TDIS 1.0 and TDIS 2.0

In order to perform electro-magnetical simulations and estimate the coupling impedance of the structure CST was used again. This software is extremely useful in this field applications because it can detect and identify the different resonant modes present in the geometry simulated.

First step was to import the original model and simulate it, taking into account to not delete the useful features.

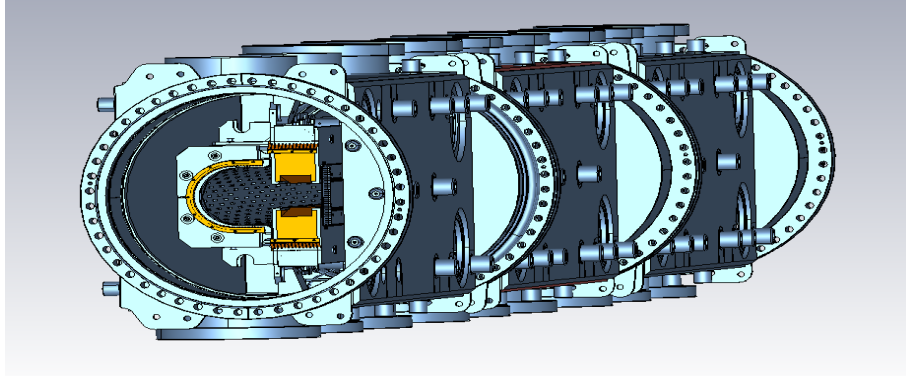


Figure 5.9. Model imported with CST before the simplification

The simplified model has already been shown in pictures 5.7 5.8. The simulations have been performed for different half-gap apertures: 5mm, 15mm and 25mm. The longitudinal impedance functions for TDIS 2.0 are reported in the plot below (Ref.[2]):

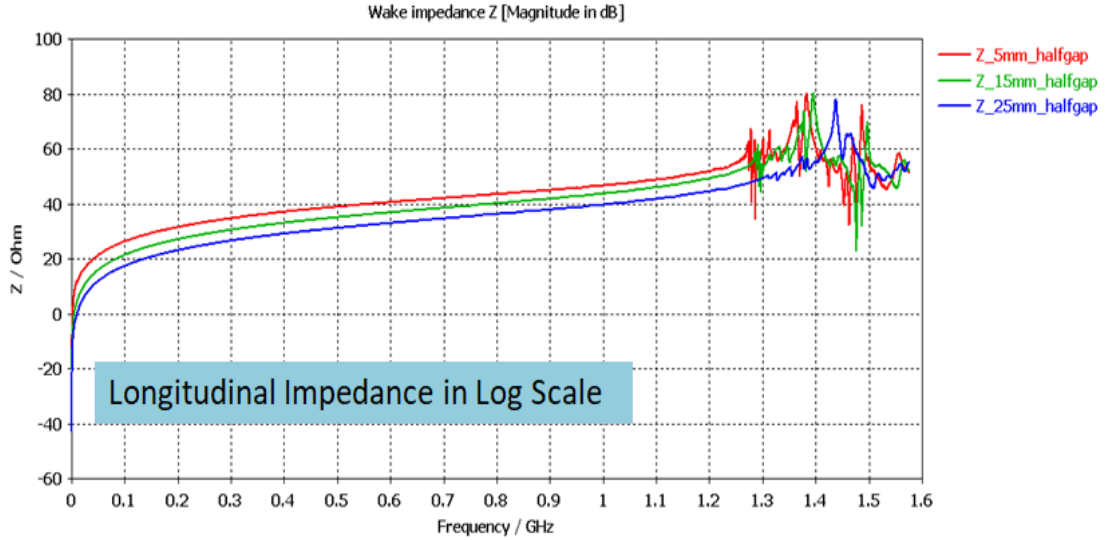


Figure 5.10

In the plot the three longitudinal impedance functions are shown in logarithmic

scale, in the scenario in which the longitudinal fingers are perfectly touching 5.12 For wider gaps the broadband contribution is visibly decreasing, the impact of the resistive materials composing the jaws is stronger when they are in tight settings: the image currents flowing in graphite and copper can induce an electromagnetic field with a bigger amplitude when these materials are closer to the beam, this effect is instead decreasing when the jaws are moving far away, leading the image currents to flow with a significant distance from the beam itself.

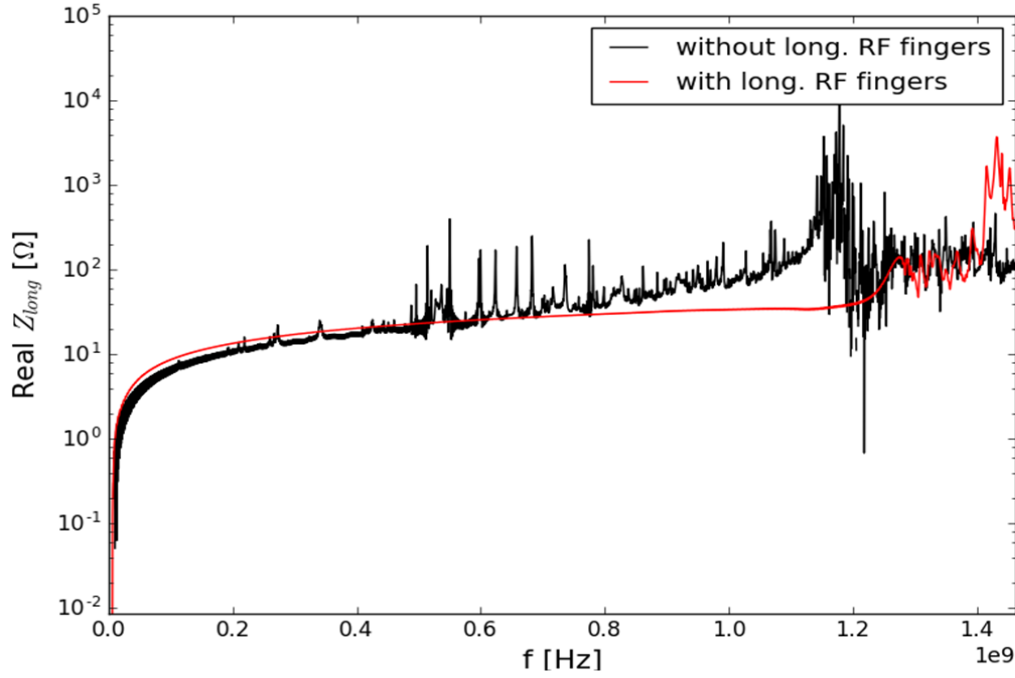


Figure 5.11. Longitudinal impedance TDI 2.0

The results in plot 5.11 are comparable to what was obtained for TDIS 1.0, the two longitudinal impedance functions have a similar behaviour both in broadband and in HOM regions.

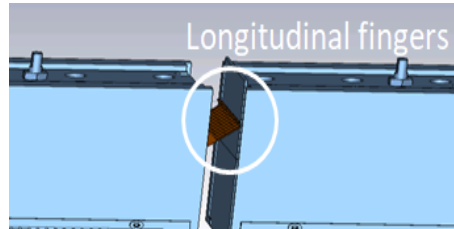


Figure 5.12

The new material used are then not consistently changing the behaviour of the coupling impedance in the scenario where the longitudinal and the lateral fingers are perfectly touching.

5.4 Longitudinal Impedance analysis in different RF fingers configurations

The RF fingers are an extremely useful tool in the coupling impedance and accelerator field but they have also negative aspects, depending on the context in which they are used. In TDIs these metallic devices are directly touching on the graphite block, which implies the possibility to have scratching phenomena and then Unidentified Falling Objects (UFO) in the beam path: this dust can quickly lead to instabilities, emittance growth and consequently beam loss. The solution to this issue could be to totally or partially remove this fingers in order to prevent this continuous scratching. In this chapter the impact on impedance of this removal will be analyzed, in order to understand whether this modification could be applied in HL-LHC project. Following the results for different half-gaps:

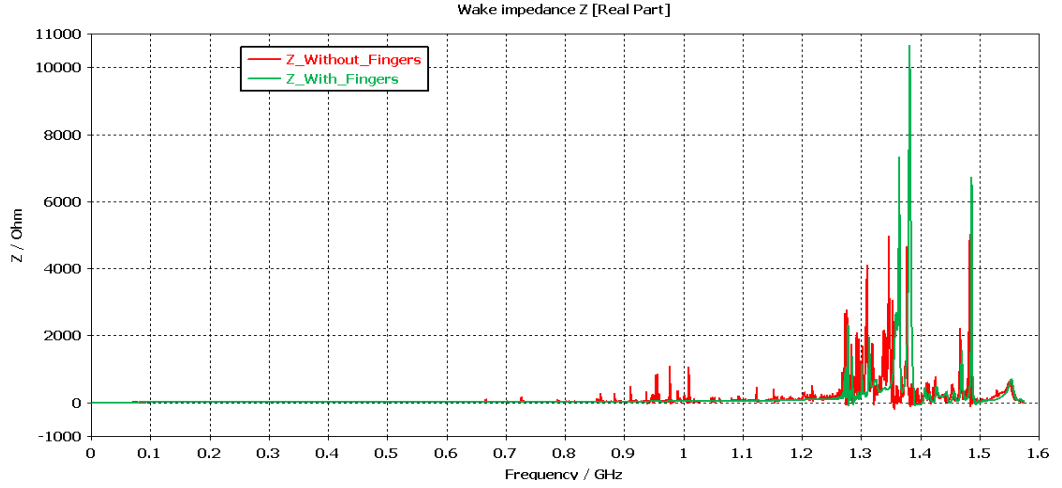


Figure 5.13. 5mm half-gap

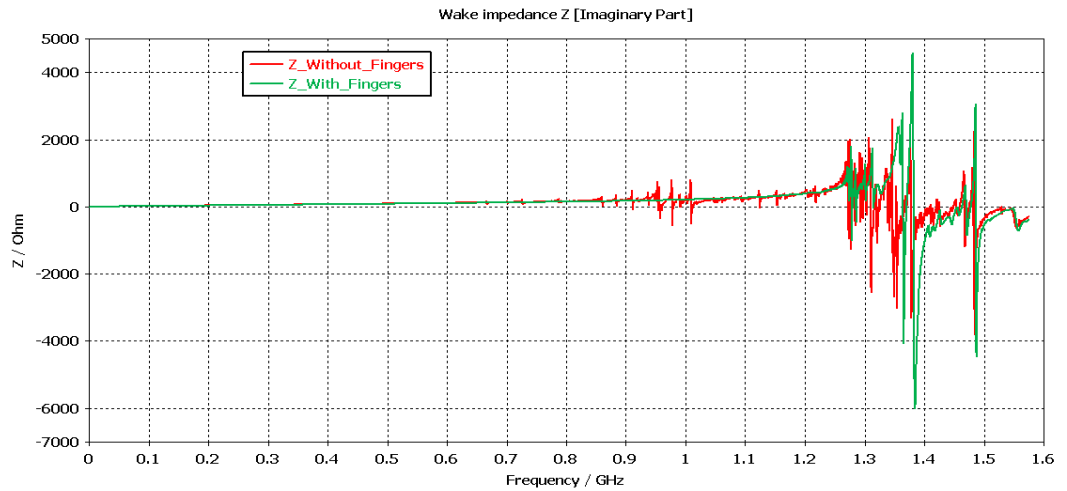


Figure 5.14. 5mm half-gap

In the 5mm half-gap configuration it is clear how much the absence of fingers is impacting the longitudinal impedance. Many resonant modes are present in the curve plotted in red, especially at lower frequencies, where the LHC beam spectrum given by a gaussian distribution with 25 ns spacing presents the higher intensity lines, which could imply not negligible losses and a significant impact on longitudinal beam instabilities.

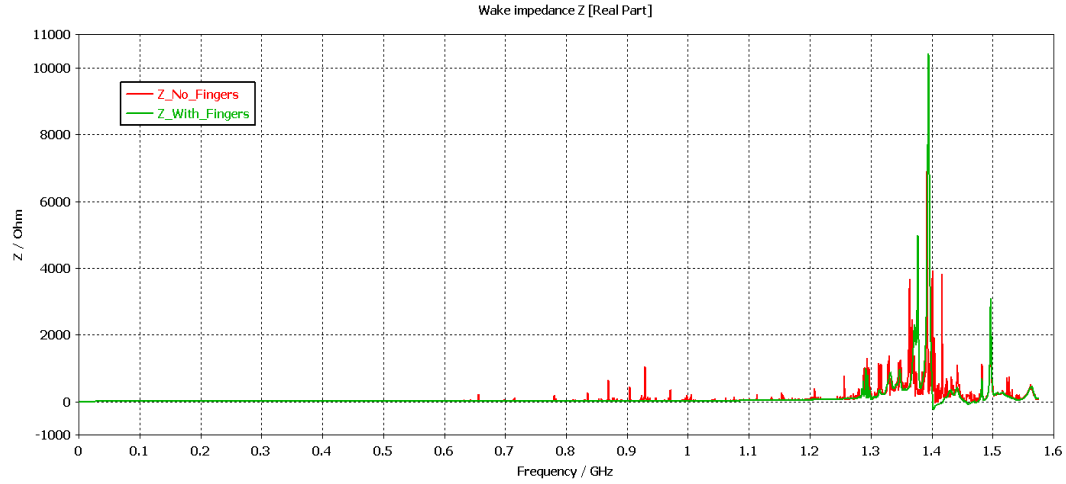


Figure 5.15. 15mm half-gap

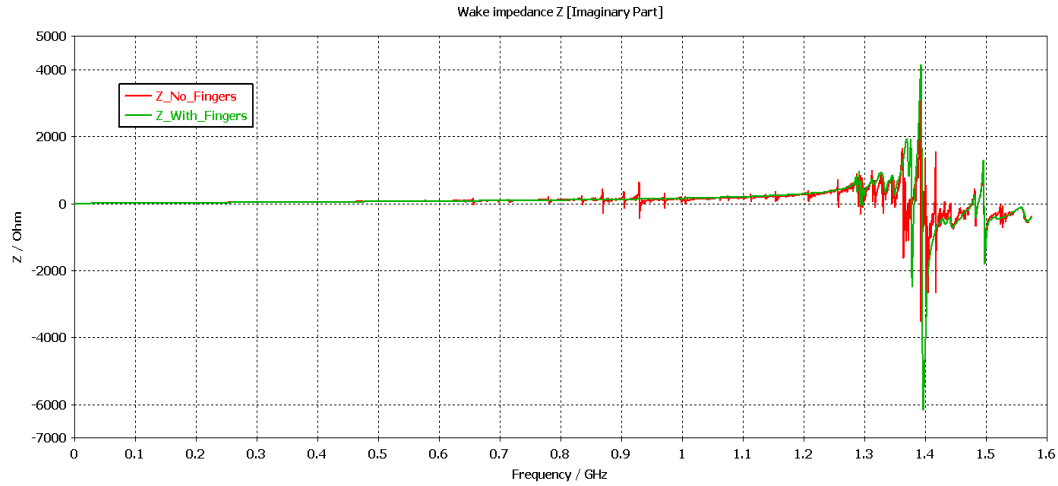


Figure 5.16. 15mm half-gap

For a wider gap configuration (15 mm) the impact on coupling impedance it is basically the same, a difference which is noticeable is how the modes below 1.1 GHz are shifted back and the modes above 1.1 GHz are shifted forward.

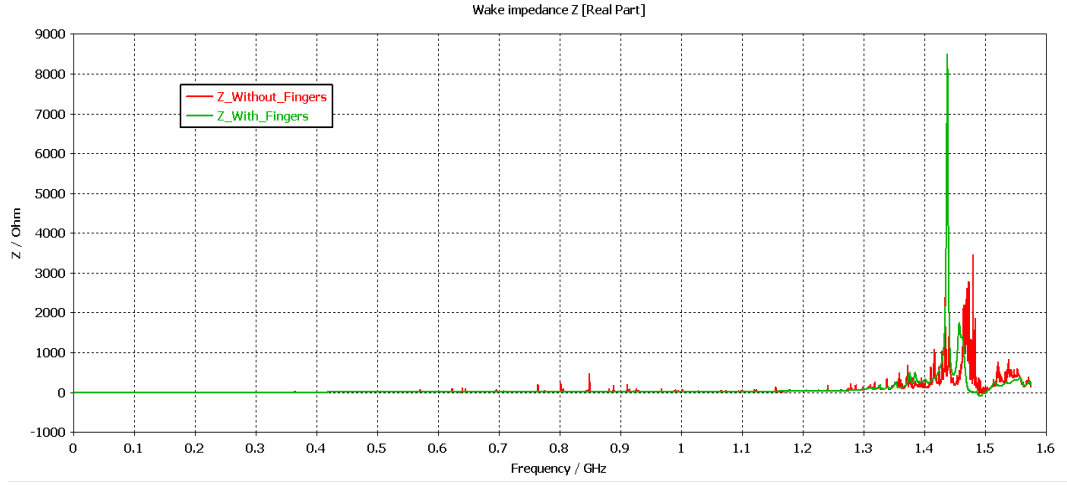


Figure 5.17. 25mm half-gap

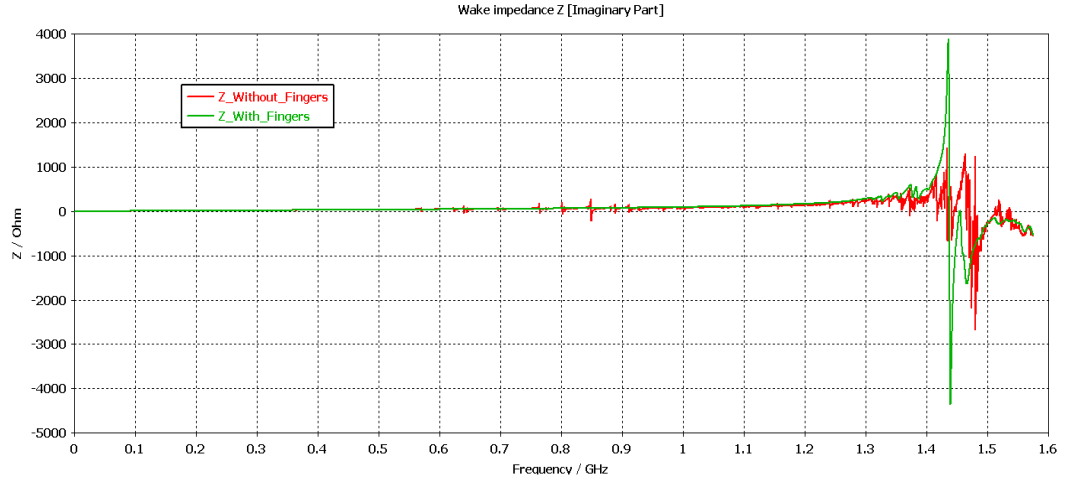


Figure 5.18. 25mm half-gap

The same pattern mentioned before is present in the scenario with an half-gap of 25mm, the mode's cluster is getting more and more splitted in two parts and the two are becoming more separated from the central frequency of 1.1 GHz, which implies that now a smaller significant cluster is pushed back in frequency: the lower the frequencies the higher the danger to hit an high intensity line of the beam spectrum, which represents a possible issue linked to beam heating. For wider gaps also the amplitude of the resonant modes seems to decrease, leading to an improved scenario which can "compensate" the cluster shifting backwards. In order to be sure about the results obtained and to confer them the necessary reliability to proceed with the analysis a match between wakefield simulations and eigenmode ones has been provided, simulating all the existing resonant modes inside the same structure. In the following plots eigenmode simulations will be plotted in blue, wakefields one in

red. The wake potential has been evaluated to a sufficient length to make it decaying of 3 orders of magnitude from the response to the stimulus, provided by the bunch passing through the structure: This wakelength doesn't make the wake potential fully converge to zero but it provides a sufficient decay to improve the reliability of the results.

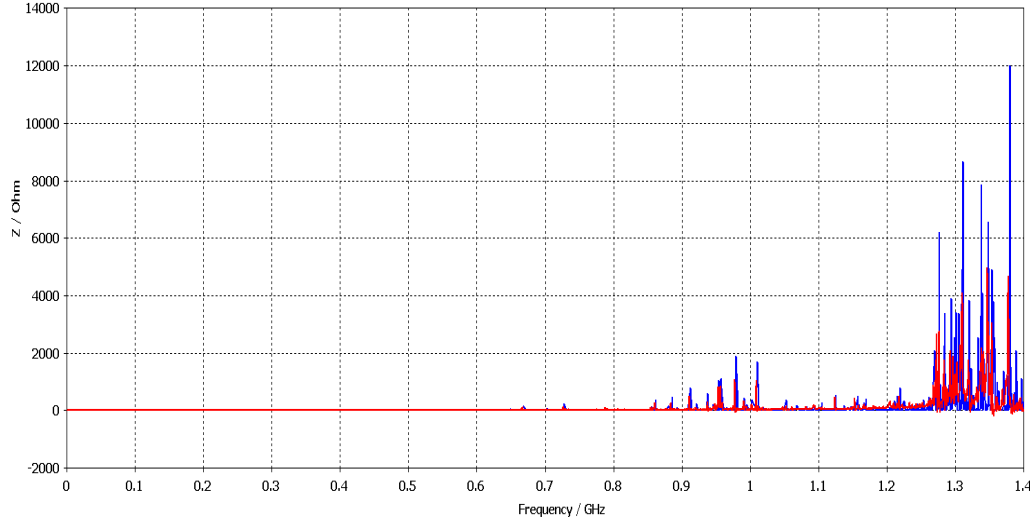


Figure 5.19. Eigenmode(blue) vs Wakefields(red) 5mm half-gap

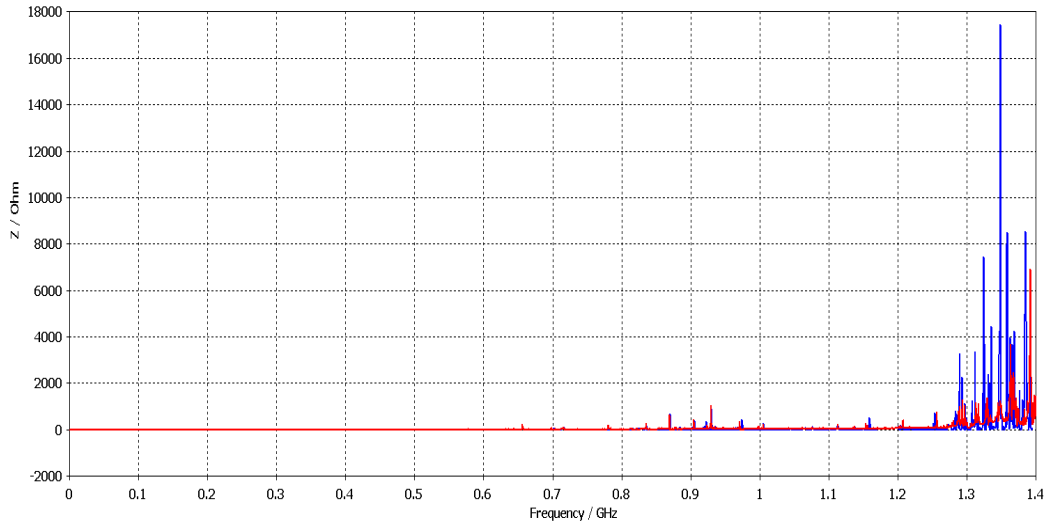


Figure 5.20. Eigenmode(blue) vs Wakefields(red) 15mm half-gap

The results obtained for 5mm half-gap simulations show a good match between the two types of simulations, both in frequency and in amplitude. In the scenario with 15mm half gap there is a good match in frequency but a discrepancy is starting to appear about the amplitudes above 1.28 GHz, leading different modes to present

higher shunt impedances than expected.

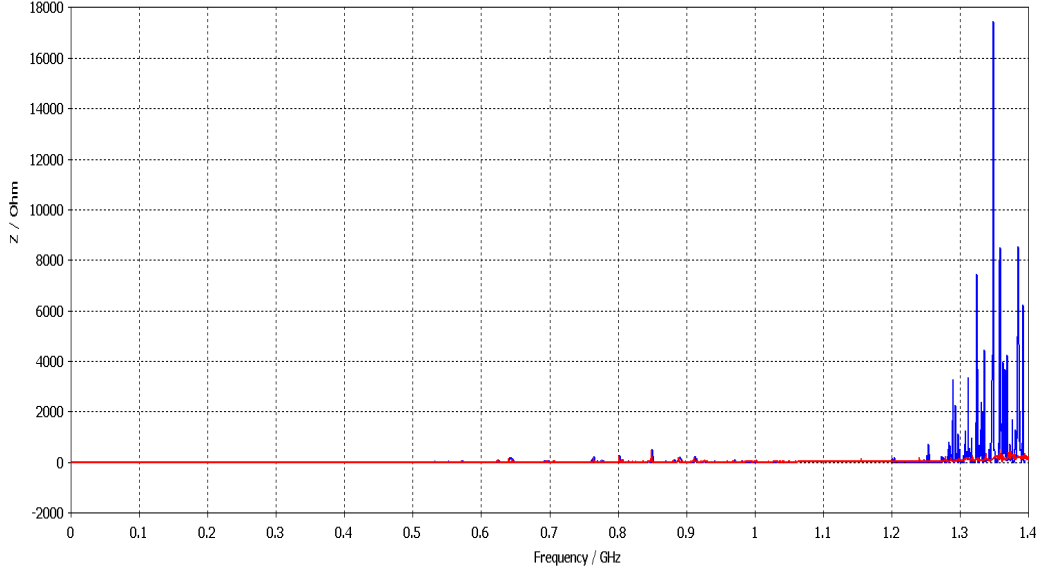


Figure 5.21. Eigenmode(blue) vs Wakefields(red) 25mm half-gap

In the scenario with 25mm half-gap aperture the discrepancy has become bigger, the amplitudes above 1.28 GHz are really starting to have a significant magnitude factor of difference in Eigenmode simulations, the shunt impedances are significantly higher than expected. This amplitude's increasing for wider gaps is related to the surface of dissipative material seen by the beam passing through the structure: when the jaws are more open the graphite starts to absorb less energy, providing a worse damping to modes amplitudes. This effect is also connected to the increase of the quality factors of the modes, which is directly connected to the wake potentials: the higher the quality factor the longer the wake will resonate, becoming sometimes almost impossible to fully simulate it. This could also explain the noticeable discrepancy, which could be solved by running extremely long and expensive simulations in terms of computational power .

The next proposed analysis is about the different impacts on impedance detected with different sets of fingers missing. During different meetings many possible configurations were discussed in order to find a compromise between impedance related aspects and mechanical possible issues: as shown before the fingers represent a valid solution under the coupling impedance point of view but sometimes providing a valid mechanical solution it is not easy as it seems. The main issue is connected to the jaw's motion system which is unintentionally able to scratch the absorbing blocks made of graphite, leading to a significant amount of powder falling on the beam path: this is a really dangerous phenomena from the point of view of instabilities. In the following pages many different scenarios will then be analyzed: TDIs without all the fingers, without just the upper row of fingers, without just the lower row of fingers.

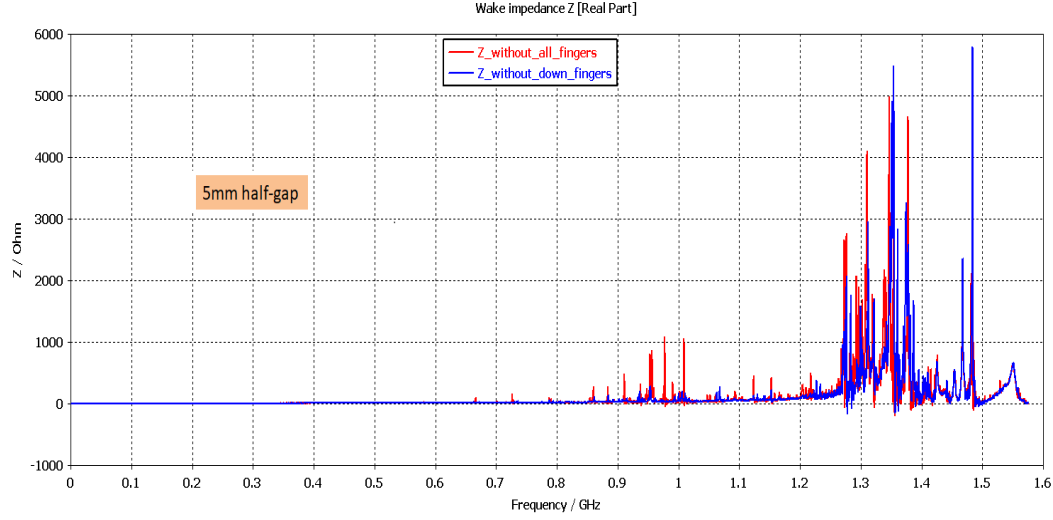


Figure 5.22

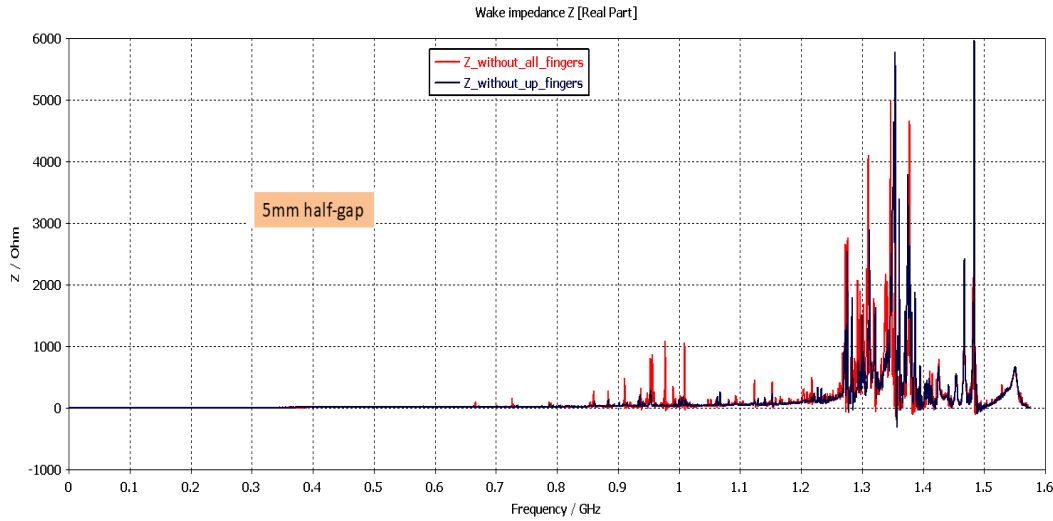


Figure 5.23

In the scenario with 5mm half-gap the differences between the blue curve and the black curve when compared to the red one show what is the effect given by different row of RF fingers missing. In the case in which just a group of fingers is removed a really close behaviour is shown above the frequency of 1.2 GHz, the peaks given by the resonant modes have a close amplitude and they are mostly at the same frequency. Below 1.2 GHz a benefic effect starts to be visible, many resonant modes have a decreased amplitude or they are totally damped.

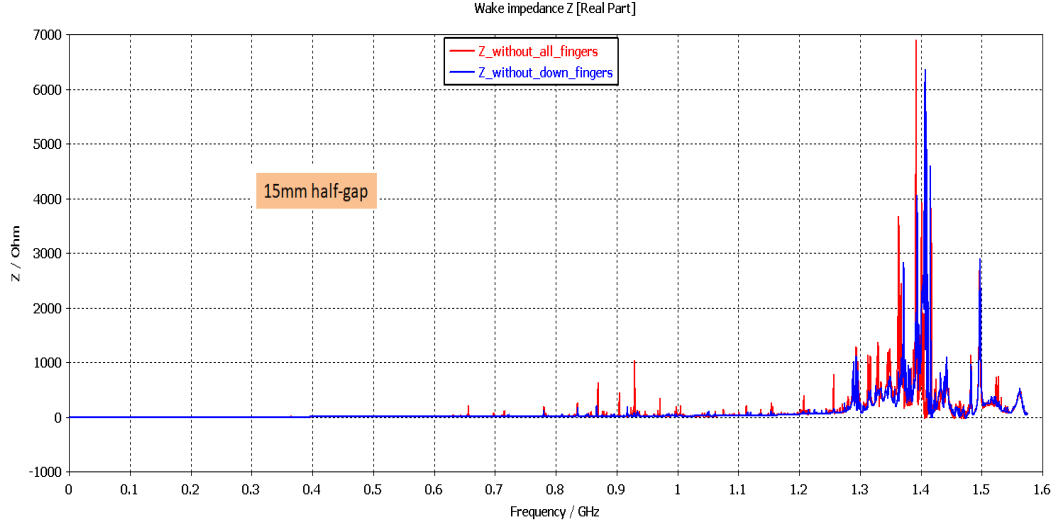


Figure 5.24

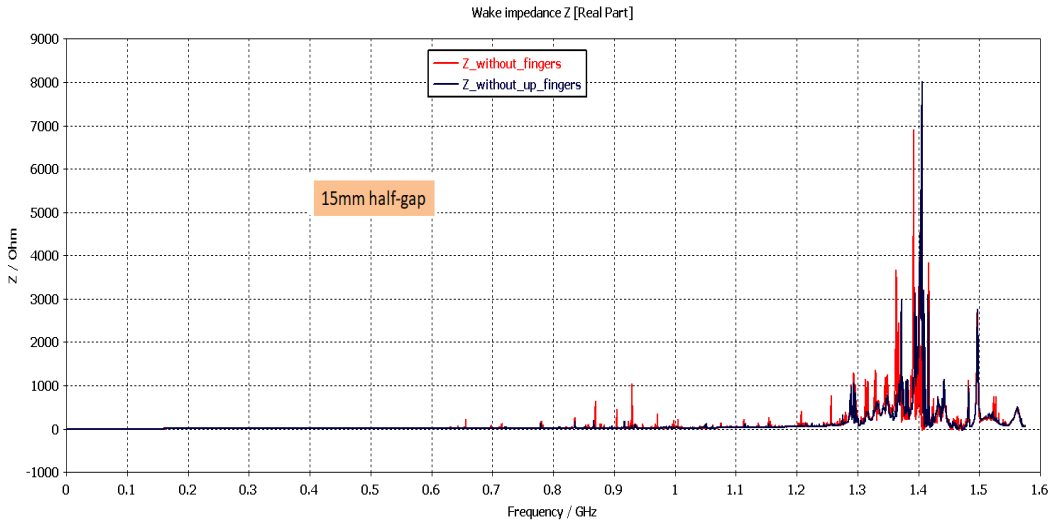


Figure 5.25

In the 15mm aperture scenario the effect noticed is the same as in the 5mm one. The smaller effect of the damping materials is visible also here, leading to modes above 1.2 GHz with sharper peaks and bigger amplitudes. The modes cluster is visibly splitting in two smaller clusters as noticed before in the scenario without all the fingers, where one is pushed forward and the other is pushed back: this leads to have many peaks at lower frequencies, where the beam spectrum lines are consistently larger and then they can cause more beam heating induced phenomena.

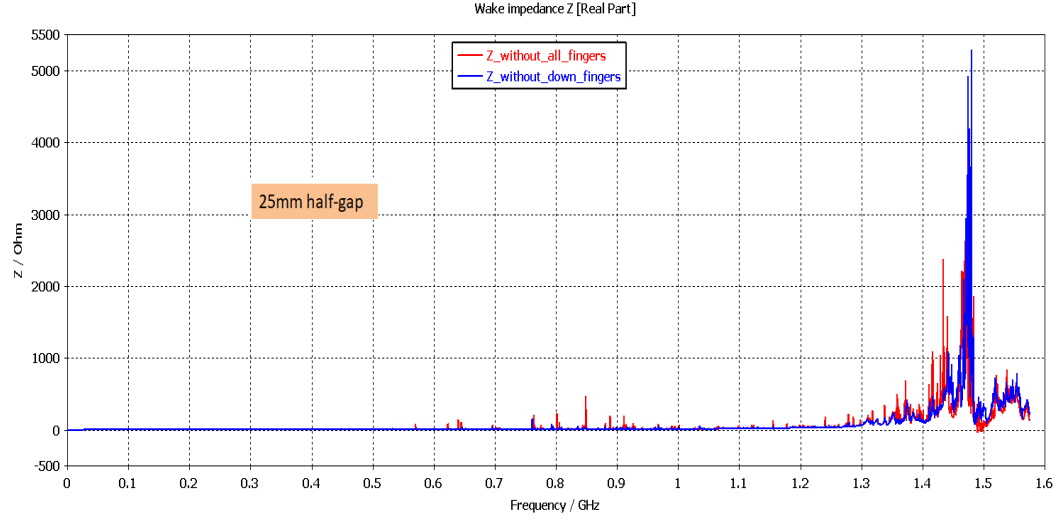


Figure 5.26

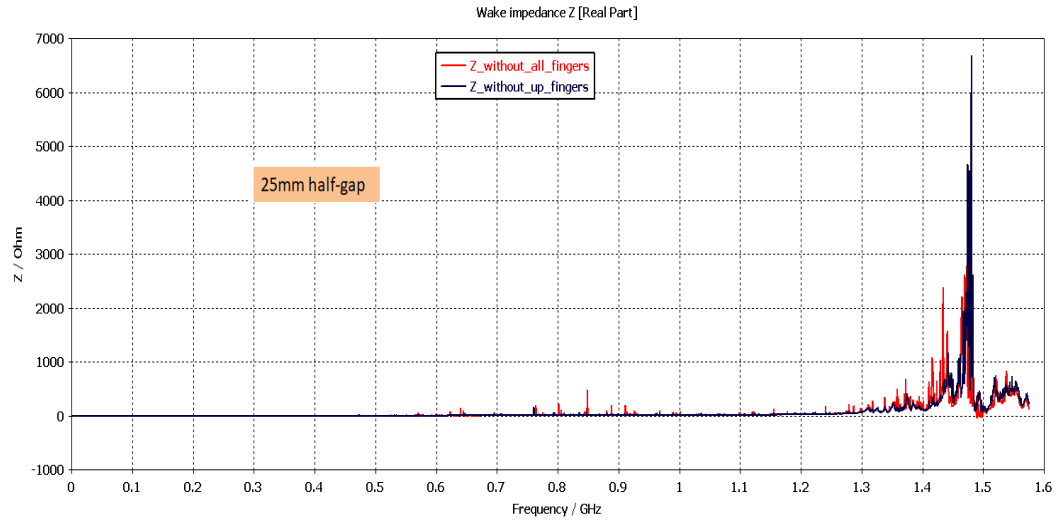


Figure 5.27

The situation shown in 25 mm half-gap aperture does not present any relevant differences with the previous mentioned scenarios, the two smaller clusters of modes are increasingly moving in opposite directions, as in the case in which all the fingers were able to touch. The modes are a bit more damped, leading to smaller amplitudes.

5.5 Estimation of power losses and beam induced heating

After all the behaviour of the coupling impedances functions have been determined in different fingers configurations now a study about power losses and beam induced heating is proposed (Ref.[2]) This effect is directly connected to the real part of the coupling impedance and the normalized beam spectrum. The estimation has been performed both in time domain and in frequency domain in order to try to match the different observations.

The beam spectrums which will be used in the next paragraphs are the ones produced by an ideal filling pattern for HL-LHC and by a real filling pattern for HL-LHC.

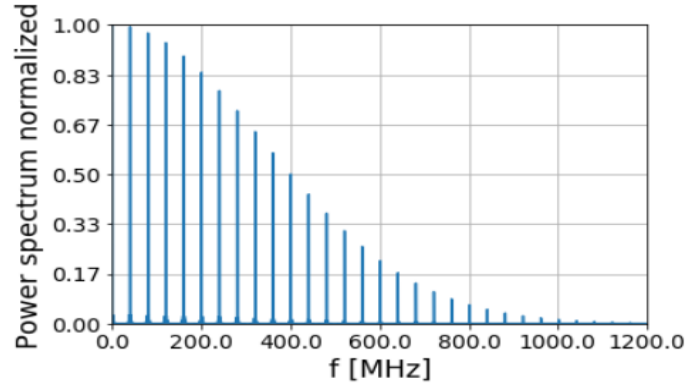


Figure 5.28. Ideal filling pattern

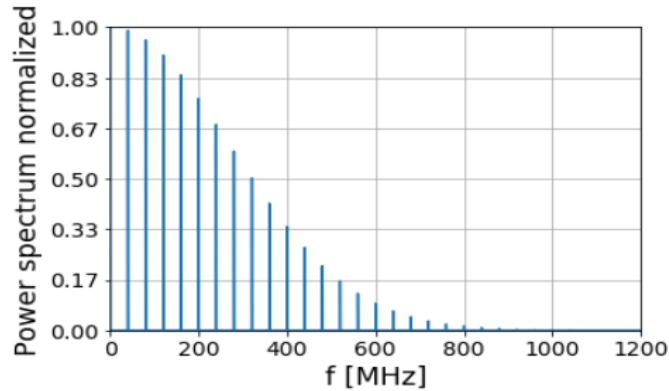


Figure 5.29. Real filling pattern

The ideal filling pattern for HL-LHC is composed by 3564 bunches with an intensity of 2.3×10^{11} and a bunch length of 9cm. It corresponds to the full machine filled, with the maximum possible number of bunches.

Table 5.1. Ideal HL-LHC filling pattern

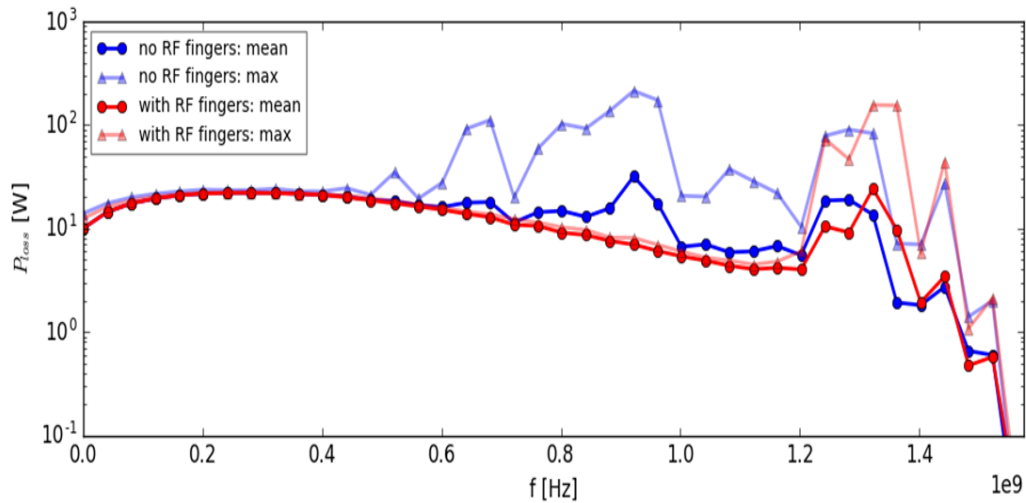
Intensity	Bunch Length	Number of Bunches
2.3e11	9cm	3564

The real filling pattern for HL-LHC is composed by 2556 bunches with an intensity of 2.3e11 and a bunch length of 9cm.

Table 5.2. Real HL-LHC filling pattern

Intensity	Bunch Length	Number of Bunches
2.3e11	9cm	2556

The losses coming from the impedance computed with the wakefields solver have been estimated with the latest one, which represents a realistic and doable filling pattern. Following the results:

**Figure 5.30.** 5mm half-gap

The result of the losses computation has been expressed as power vs frequency. In the plots four different functions are present: the red curves represent the scenario with all the fingers present and perfectly touching, the blue curves the scenario when all the fingers are totally missing. A statistical approach has been applied to determine the power losses, in fact they depend mainly on where a beam spectrum line is intersecting the real part of the impedance: the lines have been superposed on top of the biggest peaks in order to obtain the worst case scenario, represented in the plot by triangles. The circles show the values obtained by averaging the losses obtained by moving the beam spectrum lines in different positions on top of the real part of the impedance.

The maximum values obtained are mostly bigger than the average ones in all the span of frequencies and they can reach up to 100W of dissipated power per mode:

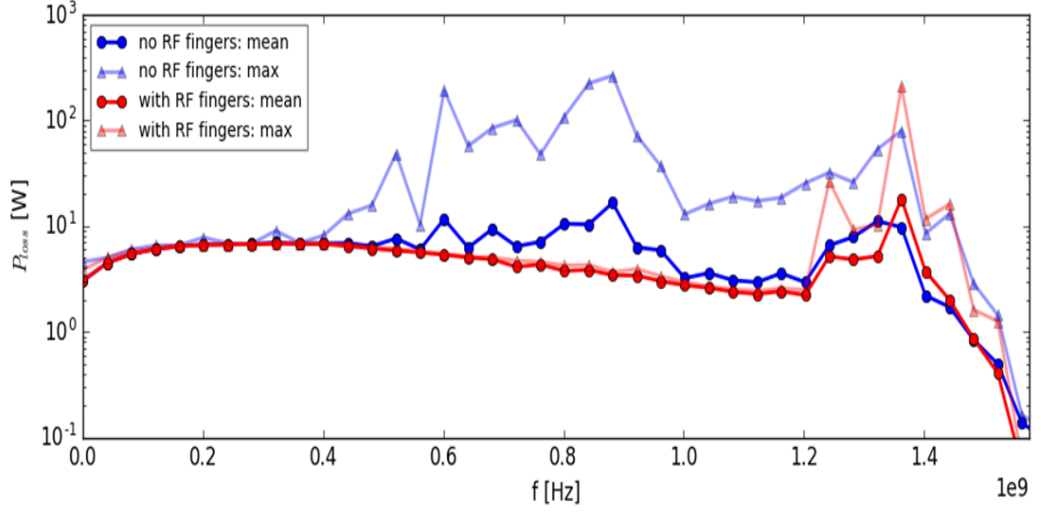


Figure 5.31. 15mm half-gap

the bigger contribution in all the frequency span comes from the blue curve, which implies that a consistent amount of power is dissipated in the regions not shielded by the RF fingers. The mean power dissipation values respects what it was shown to be the behaviour of the impedance: the red curve is flat when the fingers are shielding the structure and it shows some spikes of losses when this contact is totally missing.

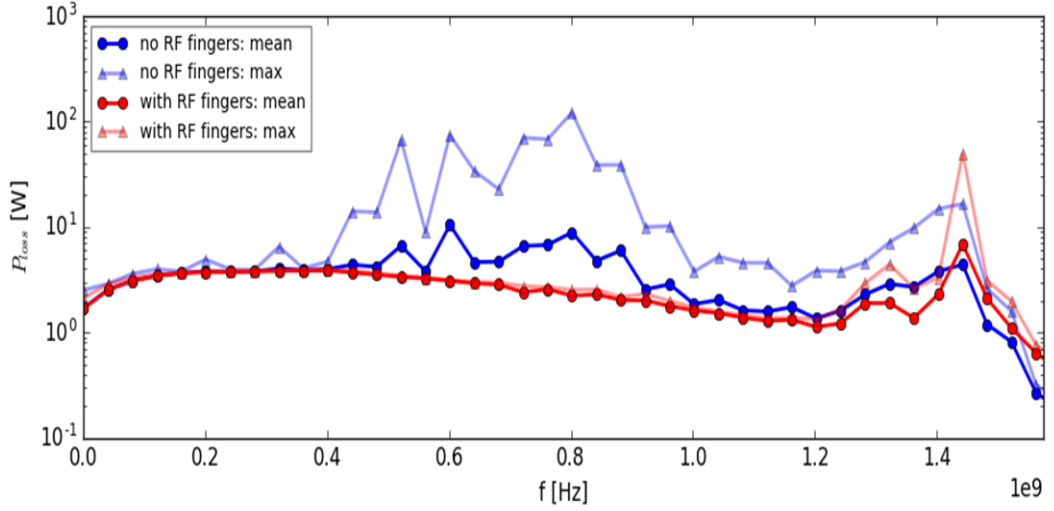


Figure 5.32. 25mm half-gap

The dependence on the gap it is not clear, it seems that the the damping effect produced by the graphite's blocks for smaller gaps it is not really affecting the power losses at the very end. This is connected to the shape of he beam spectrum, which most likely is exciting more dangerous modes in the configuration for smaller gaps.

The same analysis with the same statistical approach has been carried out also from the results coming from eigenmode solver: the resonant modes characterization obtained with this simulations are usually considered as more reliable, given the fact the in the wakefield solver sometimes the FFT is not able to determine with good accuracy the peaks of the different resonances. It is important to keep in mind also that the resistive wall effect it is not evaluable from the broadband resonator model, it has to be evaluated separately, the eigen mode solver it is not able to compute it. Following the results for an ideal filling pattern mentioned in 5.1:

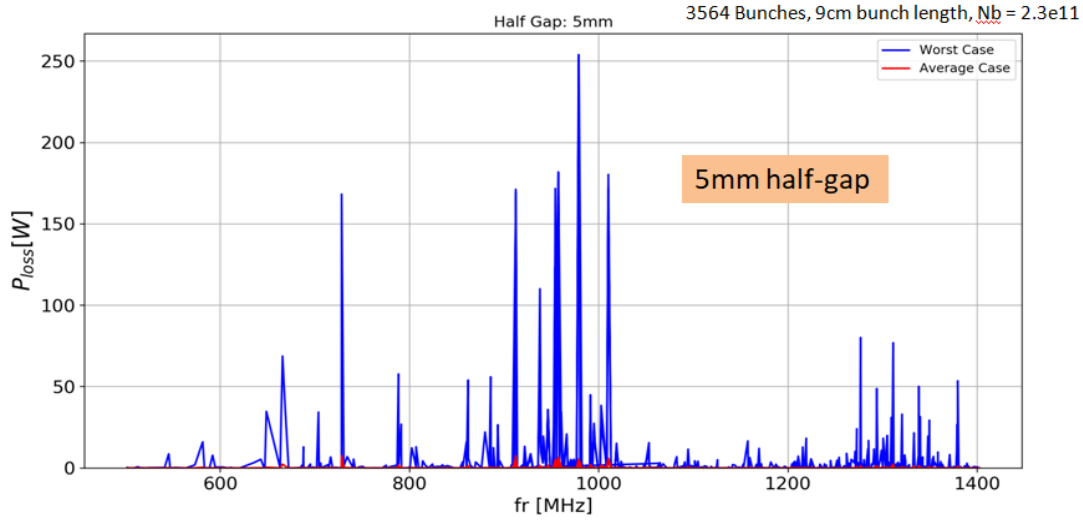


Figure 5.33. ideal filling pattern 5mm half-gap

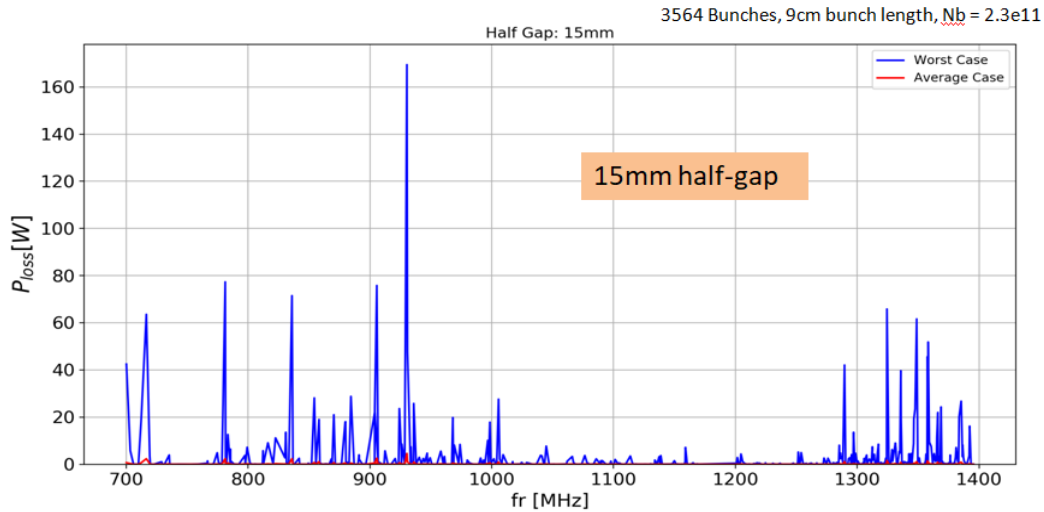


Figure 5.34. ideal filling pattern 15mm half-gap

In the ideal filling pattern scenario the losses are significantly increased: this is

due to the intensity increase of the beam spectrum lines, which directly act on the beam losses.

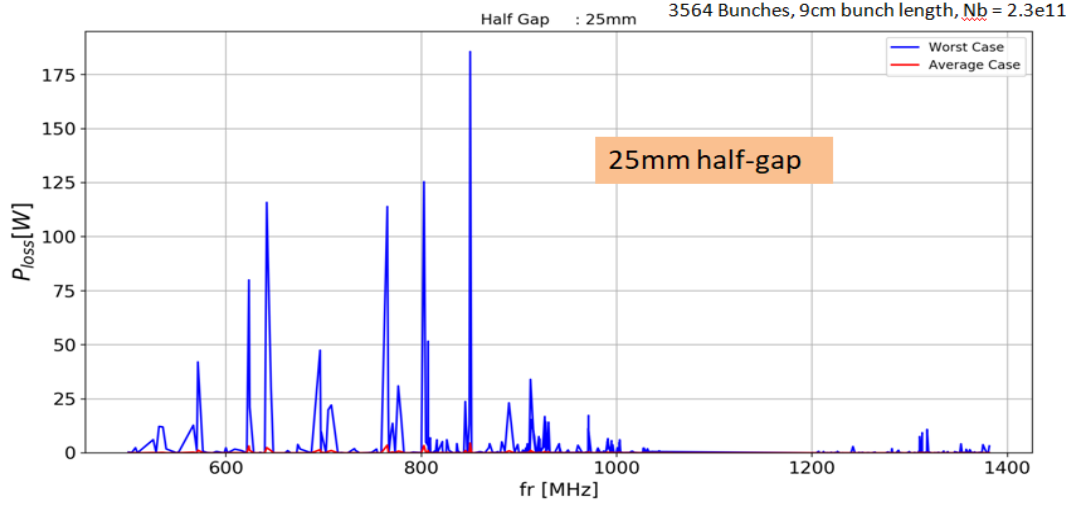


Figure 5.35. ideal filling pattern 25mm half-gap

The maximum dissipated power is now around 250 W with 5mm half-gap aperture, 160 W with 15mm half-gap and 175 W with 175 W. These numbers are clearly underlining how much the beam spectrum is connected to the losses. Following the results in the real filling pattern scenario, with a smaller amount of bunches inside the machine:

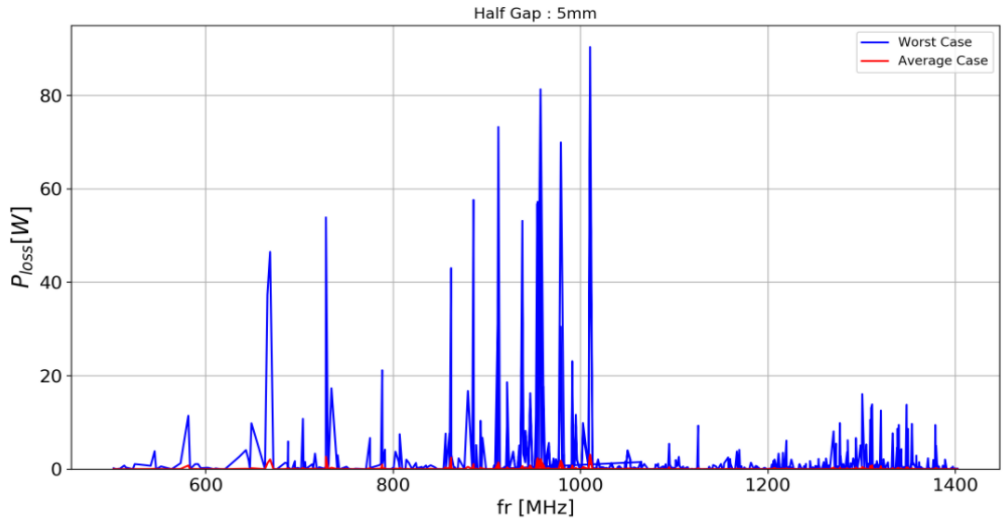


Figure 5.36. real filling pattern 5mm half-gap

The losses in the scenario with a real filling pattern are consistently smaller, considering the number of bunches which is now passing inside the machine. Once computed the spectrum looks like the one in picture 5.34 where is noticeable how the amplitude of the intensity lines is visibly reduced. This is something which leads

to a decreased amount of power dissipated, as shown in the three different scenarios for different half-gaps.

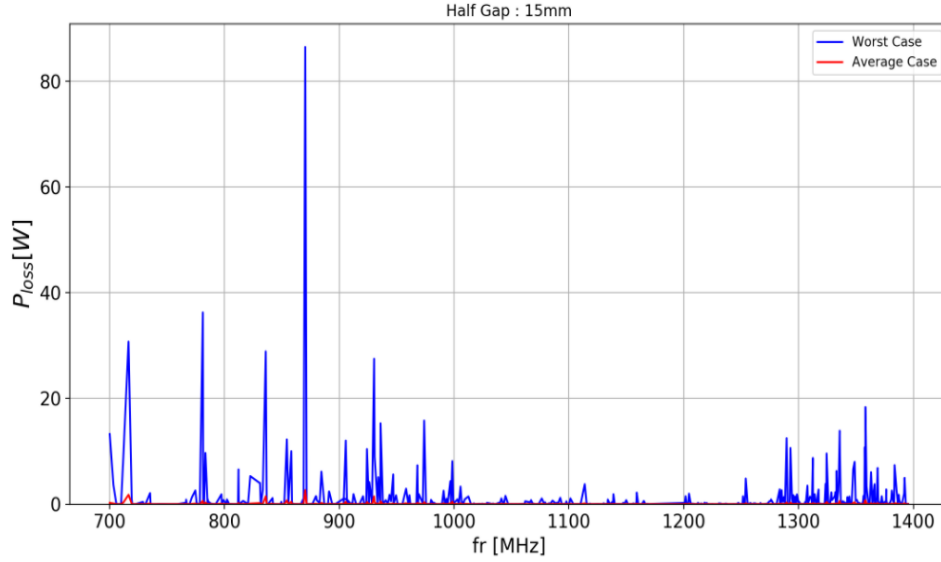


Figure 5.37. real filling pattern 15mm half-gap

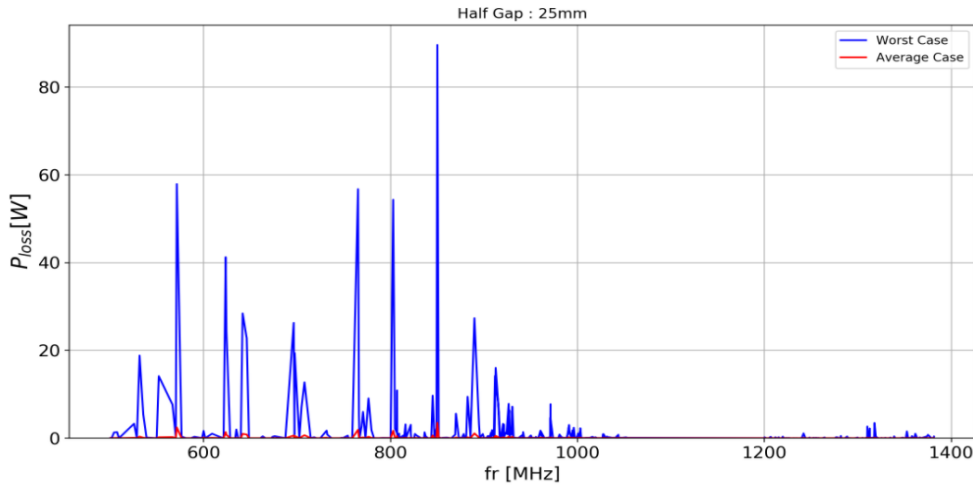


Figure 5.38. real filling pattern 25mm half-gap

The common points between the losses computed for the two different scenarios are the frequency of the peaks, whose power is scaling with the filling pattern used in the simulations. The largest amount of losses are in fact mainly present at the same frequencies, considering that the impedance is not changing for different filling patterns. By looking at the loss maps produced it is now possible to identify where the modes are located inside the structure and where precisely the highest amount of power is dissipated. By using eigenmode simulations it is possible to identify the

modes by looking at their frequencies: a 3D vision of the filling pattern is proposed by the solver both for E and H field for each of them, allowing to identify the specific field behaviour at a given frequency.

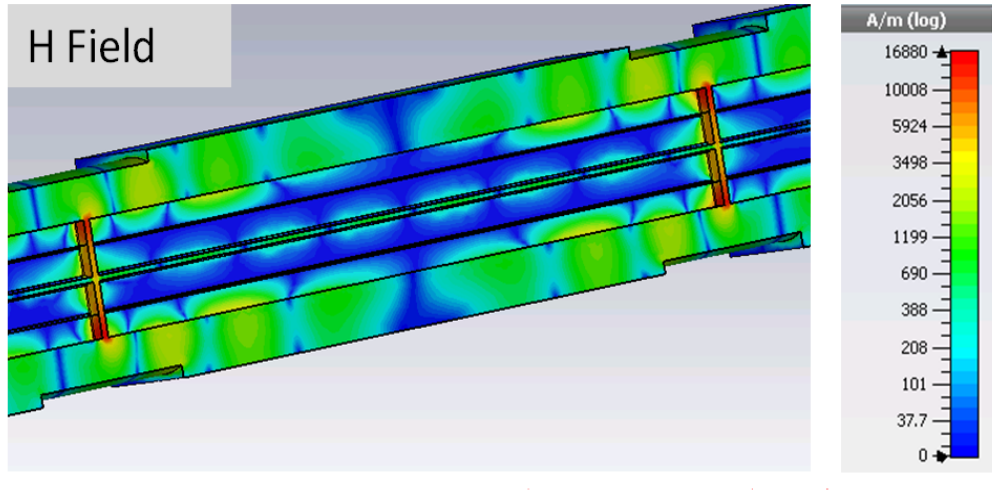


Figure 5.39. 5mm half-gap

In the case with 5mm aperture with both real and ideal filling pattern the modes corresponding to the most dangerous peaks are mainly showing field patterns as shown in picture 5.39, where the bigger concentration of magnetic field is precisely localized where the fingers are missing.

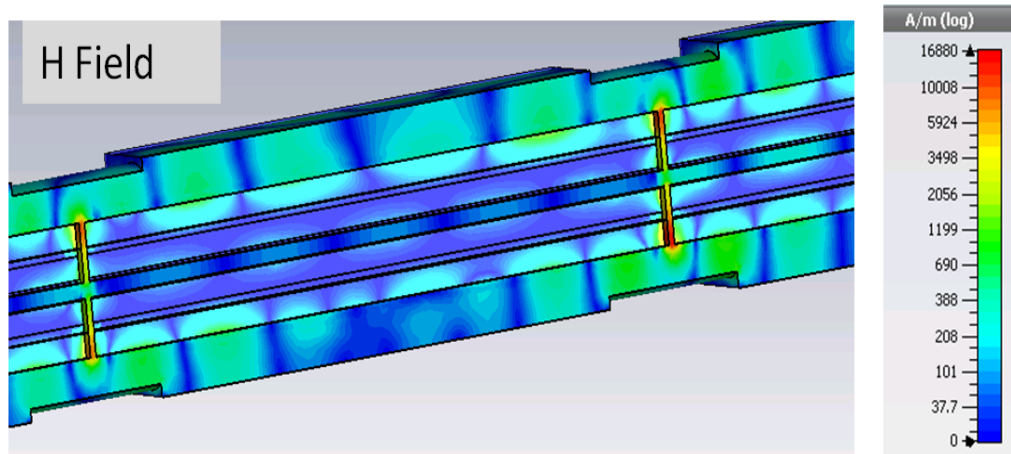


Figure 5.40. 15mm half-gap

In the 15mm and 25mm scenarios the same field patterns are present, leading to a field concentration between the different jaws.

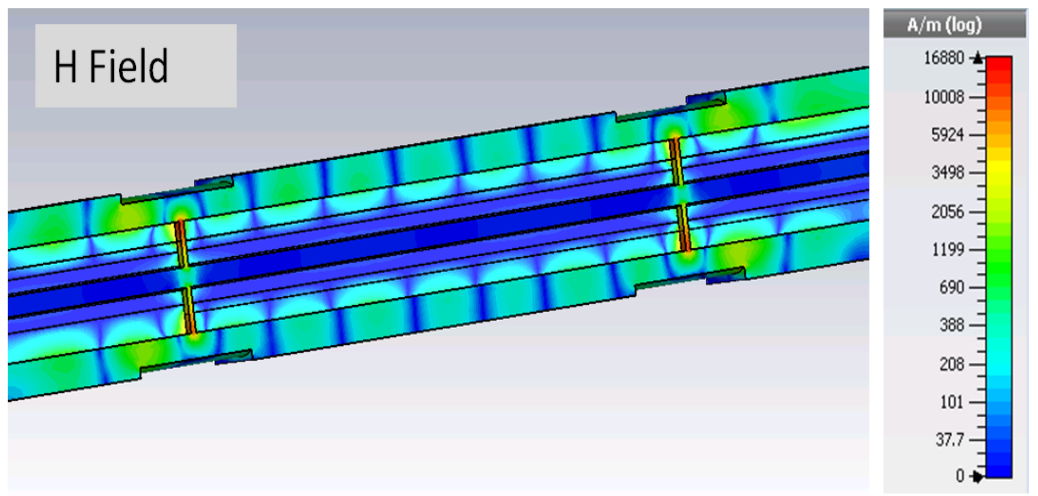


Figure 5.41. 25mm half-gap

The losses are then mostly present where the fingers are not putting into contact the jaws, leaving back small discontinuities where it is easy for the H field to penetrate and generate resonances which can propagate all along the structure. This resonances are also transporting energy in the stainless steel tank, so not all the power is really dissipated in the modes created in the finger's missing points but just the larger part of it: from the scale on the side of the pictures there is a factor 16 between the power lost between the jaws and the one lost in all the rest of the structure.

Chapter 6

Conclusions

In the beginning of this thesis LHC's collimation and protection system was introduced and its main features were shown. This system is extremely complex and it is composed of several components acting in synergy to make this amazing machine working everyday. The way in which such a complicated set of devices can act back on the proton beam is something that is needing studies and investigations, considering the large number of possible scenarios in which they can be set up. This interaction has many faces, amongst which the coupling impedance, whose analysis has been the purpose of this thesis work. In this framework several studies have been accomplished regarding the foreseen HL-LHC, first of all the analysis of the contribution to impedance given by the materials composing its prototype set of secondary collimators, which was unknown. The analysis has been done first by performing resonant wire measurements and personalised RF and DC measurements on blocks produced ad hoc, then by using IW2D and CST to crosscheck the results, at last beam measurements were done to confirm them. Their resistivities have been inferred: comparing the outcome of the different sessions TiN and MoGr are showing a good agreement but Mo is presenting a factor 5 of difference in the beam measurements. This discrepancy has been investigated by means of SEM, so far this seems to be linked to the fact that Mo is presenting a significant roughness which the other materials are not showing. In the TCSPM collimator the impact of lateral RF shielding was also investigated in different fingers failure scenarios: if these shielding devices are not perfectly touching the tank they become a potentially dangerous $\lambda/4$ resonator, unleashing electromagnetic field patterns all along the structure. About TCSPM also the impact of imperfections deriving from the jaws construction process have been investigated, leading to a contribution to coupling impedance which it has turned out to be negligible. Another device which was studied is the TDIS, whose structure was upgraded to a new one: the contribution to impedance given by its new shape has been investigated and it is mostly the same as the old one, no significant differences have been detected. Its longitudinal shielding system has been also a matter of study, considering that for the foreseen HL-LHC it was planned to remove it in order to avoid dangerous scratching collateral effects: the impact deriving from its removal has proved to be critical, as shown in this thesis work, the effect of the fields is dangerous and the losses deriving from the surface currents have been estimated in details. In the future these works will be continued, further studies

are requested and many questions still don't have a definitive answer. Thanks to tools such as CST and IW2D and to instruments such as VNAs it is possible to perform these analysis in a reduced amount of time, collecting answers and results useful for the future of accelerators such as the HL-LHC.

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