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ON TRAPPED MODES IN THE LHC RECOMBINATION CHAMBERS: NUMERICAL AND EXPERIMENTAL RESULTS

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Abstract

The recombination chamber in LHC (Large Hadron Collider) allows the separated proton beams to merge into a common vacuum chamber surrounding the interaction points. It has been subject of thorough studies concerning its interaction with the circulating beam. In this paper we present the numerical and experimental results of our investigation on an approximated geometry. We show that in the smooth transitions between pipes of different diameters a trapped mode may exist, both in the real and in the approximated geometry.

In the real structure, the mode is weak and not harmful both for the beam stability and power loss

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1 Introduction

The recombination chamber is the piece of equipment which allows the separated beams to merge into the common vacuum chamber surrounding the interaction points. Given its particular shape (see Fig. 1), it is often referred to as the Y-chamber. Before arriving at the interaction point, each beam will travel from a small beam pipe, the standard LHC vacuum chamber, through a pipe gradually increasing in diameter to finally reach the larger chamber around the interaction point, namely the transition is tapered. The intersection of the two conical tapers generates a smooth parabolic shaped wedge which makes even smoother the transition. The design and the production of these chambers is under the responsibility of the Lawrence Berkeley National Laboratory (LBNL) in the USA.

The design of these smooth transitions between two pipes of different diameters requires some careful thoughts as far as the interactions of the electromagnetic fields with the structure are concerned. The coupling impedance of such transition has been investigated numerically for both the real Y-chamber geometry (see Fig. 2) and for a simplified rectangular geometry (see Fig. 3) [1,2]. The rectangular geometry reproduces well the actual (circular) Y-chamber geometry, only when a V-shaped metal sheet is placed in front of the taper (see Fig. 3). The main conclusions have been the discovery of a trapped mode due to the taper. Such a metal sheet strongly reduces the R/Q of that mode, but does not eliminate it completely.

The relevant geometries of the device and models are described in Sec. 2. The numerical simulations results (Sec. 3) on the rectangular geometry have been checked against bench measurements which are discussed in Sec. 4.

2 The recombination chamber

The recombination chamber is located on each side of the experimental areas. The chamber is composed of a common cylinder of diameter $D = 180$ mm which then splits into two smaller cylinders of $d = 54$ mm diameter each. For the sake of the present investigation, the cylindrical geometry has been first replaced by a rectangular one, such that the diameter of the real pipe is the same as the size of the square retained (i.e. the real structure can be inscribed in the simulated one). At the junction of the two small chambers, the inner structure is continued by a kind of metal sheet. A V-shaped metal sheet reproduces well the smooth parabolic shaped wedge of the real chamber, at least concerning the electromagnetic properties of the structure. It is worth saying that rectangular tapered transitions alone is a poor representation of the actual two conical taper transition [2].

The study of the rectangular geometry has been performed mostly because for such a geometry it is easier to make a scaled prototype for bench measurements. Varying the length of the V-shaped metal sheet was also important in order to gain some insight on the physics involved. We discovered the existence of a trapped mode in the rectangular geometry which vanishes with the including of a long V-shaped metal sheet. A trapped mode also exists in the actual (circular) recombination chamber at frequencies not considered in Ref. [2]; its amplitude of that mode is luckily small and not dangerous in the LHC case. The models used in the MAFIA [3] simulations are illustrated in Fig.s 2-3 for the real (circular) and simplified (rectangular) geometry respectively.

3 Numerical simulations

3.1 Rectangular geometry

In spite of the simplified rectangular geometry, the structure remains difficult to handle with MAFIA and the simulations are very time consuming. In order to optimize both the available resources and the accuracy of the results, the following additional simplifications have been considered:

- The Y-chamber on the left of the interaction point (entry in the straight section) is treated independently from that on the right of the interaction point (exit from the straight section), although, from an impedance point of view, the two Y-chambers represent a common single structure.

- In the real structure, the trajectory of the beam is slightly inclined when going from the arc vacuum chamber into the common chamber of the straight section. This angle is very small and has been neglected in the simulations. Furthermore, it has been assumed that the beam travels in the center of the smaller pipe radius chamber.

- Because of the above approximations, the geometry of the structure is yz-symmetric, and it is thus possible to simulate only half of the structure (see Fig. 3).

From 3D simulations (both frequency and time domain), the wake potential of a Gaussian bunch (r.m.s bunch length of 1.5 cm) has been computed over a distance of 6 m behind the bunch. A subsequent Fourier transform of the wake potential yields the real and the imaginary part of the impedance for the Y-chamber. Such a procedure has been applied to the rectangular case without and with the V-shaped metal sheet (sec. 3.1.1–3.1.2 respectively) and to the real circular geometry (sec. 3.2).

3.1.1 *Y-chamber without metal sheet*

The impedance for the rectangular chamber without the V-shaped metal sheet is illustrated in Fig. 4 (real part) and in Fig. 5 (imaginary part). The pictures show a mode at 1.026 GHz trapped around the sharp edge of the tapers and weakly coupled to the modes of the wider chamber. This resonance is due to the taper joining the small vacuum chamber of the arc to the larger chamber of the common section. At frequencies lower than the first peak, the real part of the coupling impedance is greater than zero as in any transition from a narrow pipe to a wider region [4].

The longitudinal impedance of the structure can be also computed in the frequency domain (magnetic boundary conditions at both ends of the structure), resulting in a shunt impedance[1] of 54 kΩ at the trapped mode frequency and a quality factor Q of 25000. In the LHC, the revolution frequency (11 kHz) is smaller than the width of the trapped mode (41 kHz) and coupled bunch motion would be likely driven [5], if such a geometry were used.

3.1.2 *Y-chamber with V-shaped metal sheet*

The V-shaped metal sheet has been included to in order to simulate a geometry similar to the real one. The real part of the coupling impedance of the structure is presented in Fig. 6 for a 50 cm long metal sheet close to the size of the transition in the actual (circular) LBNL design. As it can be seen, the trapped mode has been strongly damped. Admittedly, the mode is much weaker and is not able to excite coupled bunch modes. Moreover, in case the lines of the bunch spectrum would coincide with the frequencies of this mode, this would induce a power deposition of the beam into the Y-chamber of the order of 50 Watts (in the LHC), which is rather small.

As far as the low frequency inductance of the Y-chamber is concerned, a complete structure (entry piece and exit piece) has been simulated. The corresponding imaginary part of the impedance is presented in Fig. 7 and yields a $Z/n \approx j$ 0.1 mΩ, which can be considered as non-negligible, but acceptable [1].

The analysis performed with the metal sheets of varying length, confirmed its role in the resulting amplitude of the trapped mode which is strongly damped in the case of long V-shaped metal sheets. This result suggested that a trapped mode, even strongly damped, might exist also in the real structure.

[1]The shunt impedance R_{sh} is defined analogously to electric circuits, i.e. $P = V^2/(2R_{sh})$ where P is the power lost in a given cavity when a voltage V is applied.

3.2 Real geometry

The wake potential for the geometry of Fig. 2 has been computed over a long distance (3 m) behind the bunch. A subsequent Fourier transform of the wake potential yields the real and the imaginary part of the impedance which are shown in Fig. 8.

A weak trapped resonance shows up around 4.5 GHz, which is a frequency greater than the cut-off of the smaller tubes (4.42 GHz for TM modes). It is apparent that with the smooth parabolic shaped wedge transition the mode propagates in the wider common chamber. Its amplitude does not concern the beam dynamics since it is characterized by a small R/Q value and its frequency is high compared to the LHC bunch spectrum (nominal r.m.s bunch length of 7.5 cm). The broad band impedance [5] of the mode is also very small, namely $Z/n \approx j$ 75 $\mu\Omega$.

4 Experimental investigation for the rectangular geometry

Bench measurements have been performed to assess the numerical results. For practical reasons, we consider a rectangular scaled model of the LHC recombination chamber. Figure 9 shows half of the whole structure and the yz-plane is the symmetry plane. From the squared common region (of side $a = 66$ mm), two (squared) beam pipes of side $b = 18$ mm take off; the transition taper is long $c = 85$ mm. The structure of Fig. 9 is placed inside a box of squared cross-section of side a.

A wire is located on the beam trajectory (light blue line in Fig. 9) and it results in a coaxial transmission line. The energy lost by a relativistic particle traveling in the structure can be estimated from the transmission attenuation between the two ports connected by the wire. Therefore any trapped mode possibly excited by the beam in the transition of Fig. 9 can be excited by the wire as well.

4.1 HFSS Simulations of the scaled prototype

To check the feasibility of the measurements, a campaign of HFSS [6] simulations has been performed on the actual bench set-up (Fig. 9) with a “perfectly conducting” wire of square cross section (2 mm $\times$ 2 mm). The taper alone (no metal sheet) has been studied first since a strong trapped mode was expected. A typical result is shown in Fig. 10 where the significant notch in the S_{12} at 2.737 GHz is a clear sign of the presence of the mode. The simulated structure has no loss mechanism since the structure is perfectly conducting, and the minimum S_{12} is approaching a value close to zero ($-\infty$ in a db scale). In the real prototype (brass and aluminum, see Sec. 4.2) the resistive losses wide the resonance, but they do not eliminate it.

It is interesting to look at the field configuration inside the structure. When the transmission is minimum, the power entering the structure from the input port (lower part of Fig. 11) is reflected at the taper and the field has a typical standing wave pattern as in Fig. 11a which shows the maximum amplitude of the electric field. The field is concentrated around the wire, as expected for the fundamental mode in any coaxial structure. There is also a strong field concentration close to the wedge of the taper which confirms the existence of the trapped mode; a very small amount of field reaches the end of the two small waveguides indicating big losses for the beam at that frequency. The field pattern is completely different at 2.5 GHz, i.e. in the middle of the transmission plateau of Fig. 10. The field is guided by the coaxial wire and there is a full transmission of power between the two ports. The electric field amplitude is maximum along the wire (Fig. 11b) and it is inversely proportional to the distance from the wire. A beam traveling along the wire direction will not excite any trapped mode at this frequency.

In conclusion, the trapped mode is present also in the numerical analysis of our bench set-up and it can be measured by looking for a strong notch in the transmission coefficient of a coaxial wire structure.

4.2 Experimental set-up

The prototype built is relatively simple and cheap; its dimensions have been chosen to be a smaller model of the recombination chamber and the relative ratios among the different parts have been kept as in the real design. The common region is modeled by an aluminum box with square cross-section (33 mm $\times$ 33 mm $\times$ 1 m) and the tapered region is obtained with a brass transition, as shown in Fig. 12. A copper wire of 0.4 mm of diameter is stretched between the two connectors in the lower part of the brass taper; matching resistors are also included and their values are chosen according to Appendix 5.

An important issue for getting reproducible results, is to assure good contacts; the contact between the brass transition and the external box is improved by using proper RF-fingers (the RF contacts of Fig. 12a). The two halves of the structure are also pressed one against the other by external screws.

Two different measurements have been performed and will be discussed in details, namely the taper alone, and with a V-shaped metal sheets obtained from a 0.02 mm thick copper foil.

4.3 Experimental results

A first set of measurements has been performed on the tapered transition alone, i.e. without the metal sheet. The transmission coefficient S_{12} is reported in Fig. 13. A strong notch at 2.753 GHz indicates the trapped mode; such a frequency is close to the numerical predictions, that is 2.737 GHz from HFSS. The fluctuations on the flat part of the S_{12} may depend on the non perfect matching. The growing of S_{12} around 3 GHz (Figs. 13–14) is due to the parasite capacitance and inductance of the carbon resistors which become relevant at these frequencies.

In Fig. 14 we show results obtained with a 20 cm long V-shaped metal sheet soldered on the taper. This length has be chosen to reproduce the influence of the parabolic transition wedge present in the actual design. The measurements show a complete suppression of the trapped mode, while the simulations predicted a residual effect. Our measurement sensitivity was not high enough to measure such small effects in an unambiguous manner. Introducing some perturbation (metal object) close to the taper, we observed clearly a small effect, due to the electromagnetic energy trapped in the vicinity of the taper.

5 Conclusion

In this paper we present the results of a numerical and experimental study on the recombination chamber of LHC. To understand the electromagnetic interaction between a particle beam and that structure, we studied a simplified rectangular geometry which shows the existence of a trapped mode close to the vertical wedge separating the two beam tubes. Such a study demonstrates that its amplitude is damped when a smooth transition wedge is present (V-shaped metal sheet). Similarly the real structure, where there is a parabolic wedge shaped transition, shows a trapped mode at high frequency; its amplitude is weak and there are not dangerous effects in the LHC beam dynamics.

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[6] See World Wide Web address, `www.ansoft.com`.

Appendix: Resistive matching networks for the bench set-up

As discussed above, our bench set-up is a coaxial line obtained by inserting a copper wire in our Device Under Test (DUT). The transition between such a coaxial line and the cables connecting the Vector Network Analyzer (VNA) is not automatically matched. Let us assume that the coaxial line has a characteristic impedance of Z_c and that the VNA is calibrated, i.e. the cables have the same impedance $Z_0 = 50\ \Omega$ ($< Z_c$). The measurement set-up schematically looks like Fig. 15, where the transition between the different transmission lines is done with matching networks to minimize (ideally to avoid) reflections. In the ideal case, a wave going from the coaxial line of the DUT into the cables (see dashed arrows in Fig. 15) is not reflected back and this situation is called "internal matching". Similarly a wave traveling from the cables to the coaxial line (solid arrows in Fig. 15) is not reflected either and we will refer to it as "external matching".

Different types of matching networks are possible, but we will focus only on resistive ones. They are easy to build and they work well at low frequencies; at high frequencies, the matching depends on the quality of the resistors (parasite capacitance and inductance). For narrow band (or high frequency) measurements, better matching can be achieved by conical transitions (which have to be designed "ad hoc").

To achieve both "internal" and "external" matching, a network of at least two resistors is needed. Anyway to prevent only multiple reflections at the ends of the coaxial line without caring of the reflected signal at the transition from the cable to the coaxial line, only one resistor is enough. The single resistor matching network has also the advantage of having a wider bandwidth than the networks with multiple resistors. In other words, the condition for "internal matching" only can be satisfied with a single resistor such that

$$Z_c = Z_0 + Z_{match}, \tag{1}$$

where the matching resistance Z_{match} is connected as in Fig. 16. Equation (1) simply states that the impedance seen from the coaxial line looking toward the cable is equal to impedance of the incident wave.

To measure Z_c we used a kind of "Time Domain Reflectometry", that is observing the signal reflected by the unmatched transmission line with a synthesized step excitation (called "low frequency step" in the VNA jargon). The calibrated S_{22} for the (unmatched) coaxial line is shown in Fig. 17a, where the different "stairs" are the multiple reflections at the opposite end of the structure (HP8753D with time domain option). From the amplitude $\Delta\Gamma$ of the reflection coefficient it is possible to get the impedance of the line Z_c

$$Z_c = Z_0 \frac{1+\Delta\Gamma}{1-\Delta\Gamma} = Z_0 \frac{1+0.714}{1-0.714} = 299\ \Omega, \tag{2}$$

since $Z_0 = 50\ \Omega$. According to Eq. (1), $Z_{match} = Z_c - Z_0 = 249\ \Omega$; for practical reasons, then, the two matching resistors actually soldered between the wire and the connectors are of 240 Ω and they are visible in Fig. 12b. The reflection coefficient of the matched line is shown in Fig. 17b, where the multiple reflections disappeared at the price of an increased reflection of the signal coming from the network (about 80% of the input signal is reflected versus only 65% without resistors on the wire).

List of Figures

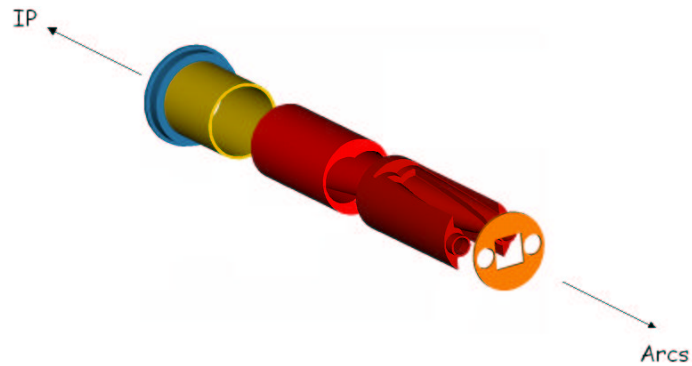

Figure 1: The beam tube transition where two small beam tubes (coming from the arcs) merge to a single large one at the Interaction Point (IP).

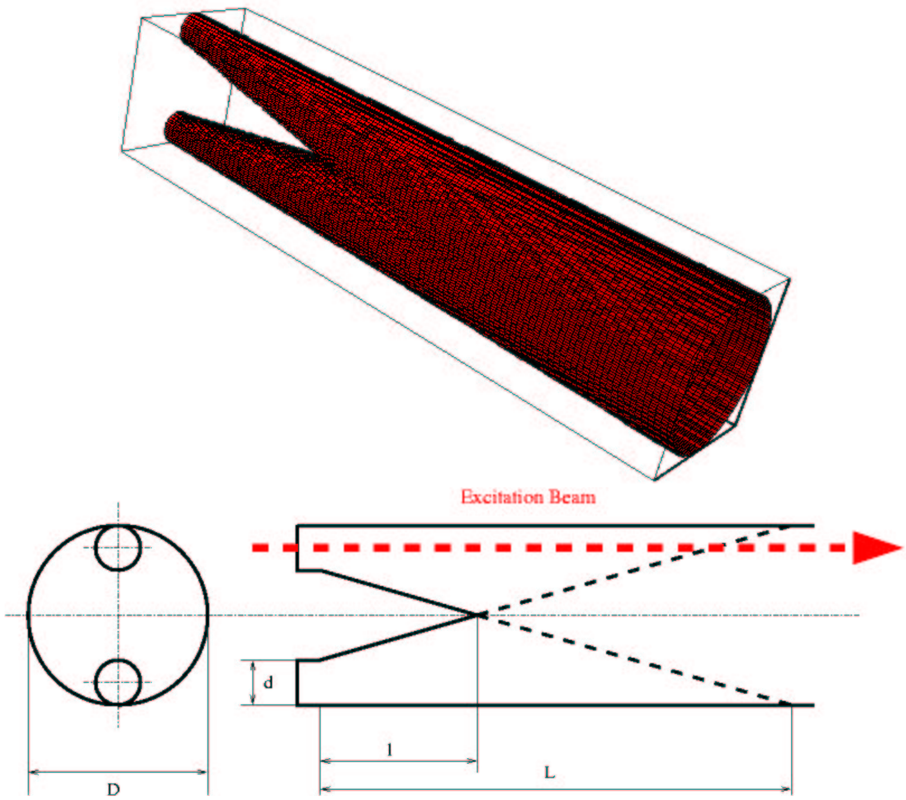

Figure 2: Relevant geometry for the Y-junction. The upper picture shows the model used in the MAFIA simulations (circular geometry). The cross sections are shown in the lower picture ($L = 852\ mm$, $l = 260\ mm$, $d = 54\ mm$, $D = 180\ mm$) where the arrow indicates the path of the exciting beam.

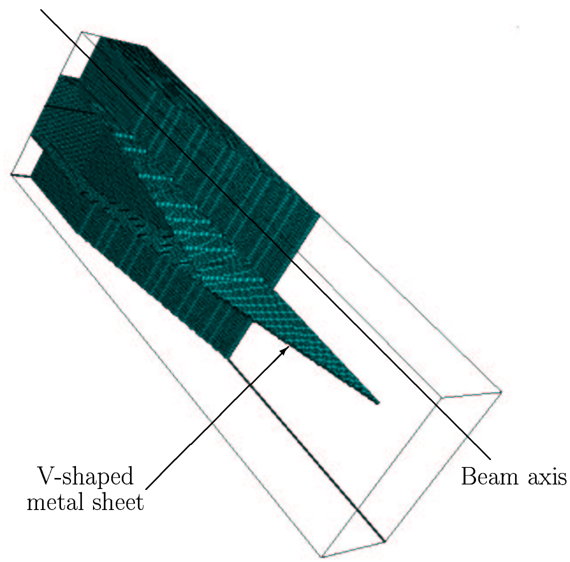

Figure 3: Rectangular model of the Y-chamber used for MAFIA simulations (half structure because of symmetry).

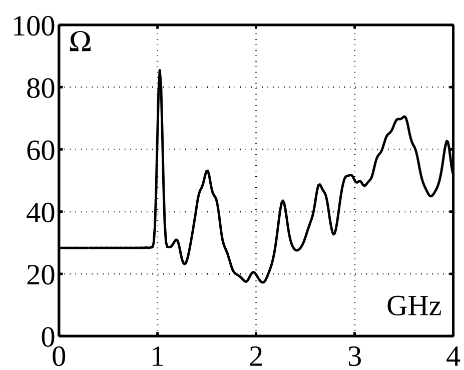

Figure 4: Real part of the longitudinal coupling impedance for the Y-chamber (no metal sheet, rectangular shape).The sharp resonance is at 1.026 GHz.

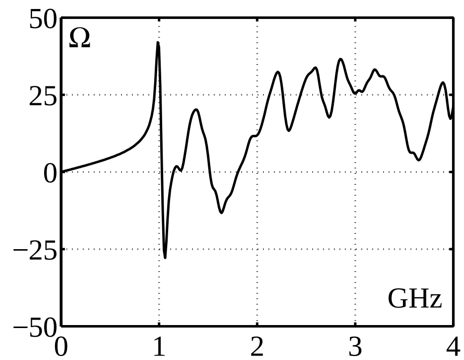

Figure 5: Imaginary part of the longitudinal coupling impedance for the Y-chamber (no metal sheet, rectangular shape).

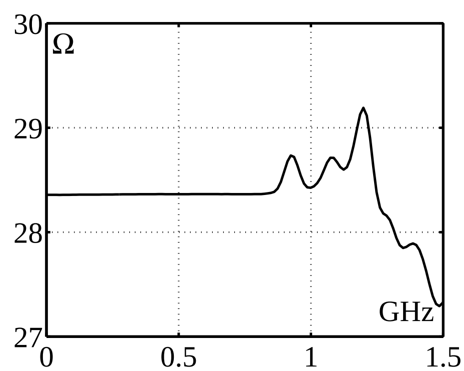

Figure 6: Real part of the longitudinal coupling impedance for the Y-chamber with 50 cm metal sheet (rectangular shape).

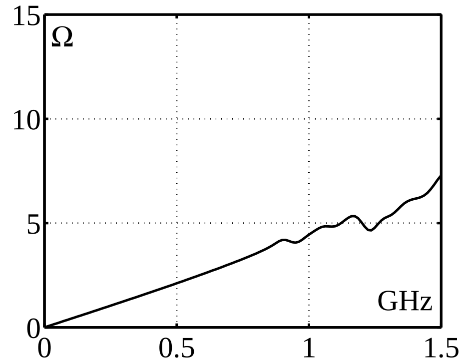

Figure 7: Imaginary part of the longitudinal coupling impedance for the Y-chamber with metal sheet (rectangular shape, global structure).

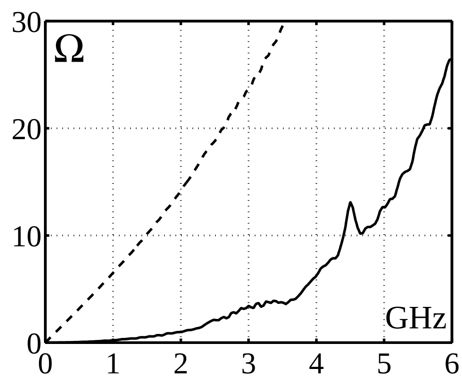

Figure 8: Real part (solid line) and imaginary part (dashed line) of the impedance for the Y-chamber (actual structure, circular shape).

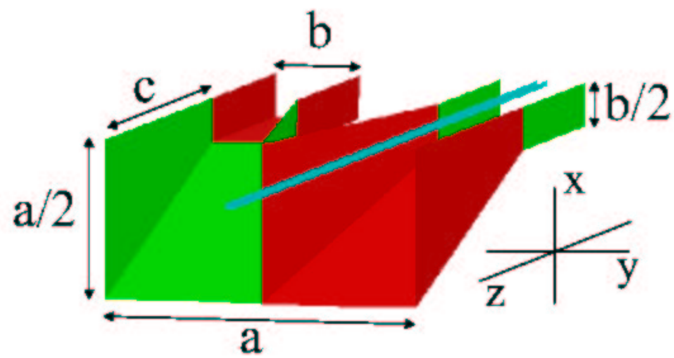

Figure 9: Bench measurement geometry. The small tubes represent the two beam pipes merging into the common region through the tapers. The light blue line represents the wire used to simulate the behavior of the beam both in the bench measurement and in the HFSS simulations (see sec. 4.1). Only the lower half structure is shown and there is no metal sheet ($a = 66$ mm, $b = 18$ mm, $c = 85$ mm).

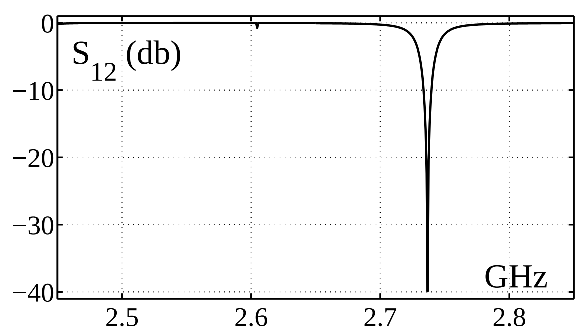

Figure 10: Transmission coefficient at various frequencies from HFSS simulation. The structure is ideal, i.e. no losses and perfect matching; thus the S_{12} is unitary (0 db) except close to the resonance where the trapped mode is (2.737 GHz).

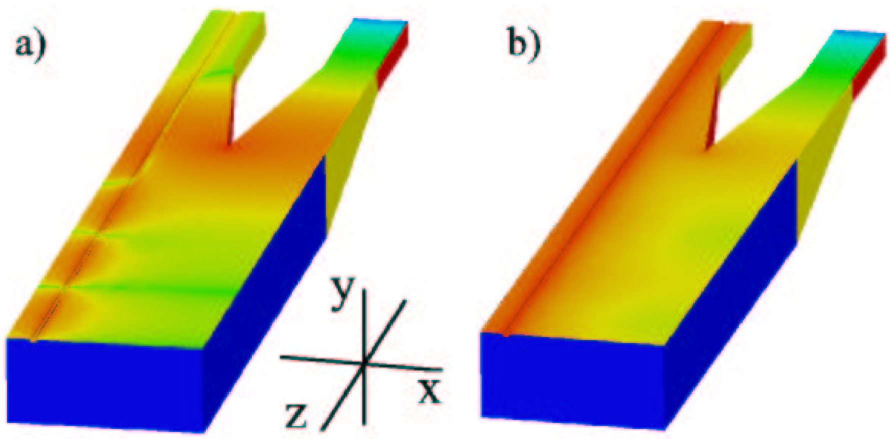

Figure 11: Amplitude of the electric field (maximum value). The left plot is the field at 2.737 GHz where the transmission notch is; the bigger part of the e.m. power is in the trapped mode at the wedge. On the contrary in the right plot (2.5 GHz) the field is propagating and it remains close to the wire. The (logarithmic) color scale is such that the maximum amplitude is red and the minimum one is blue (scaling as the rainbow colors). The input port is at the bottom in both the pictures.

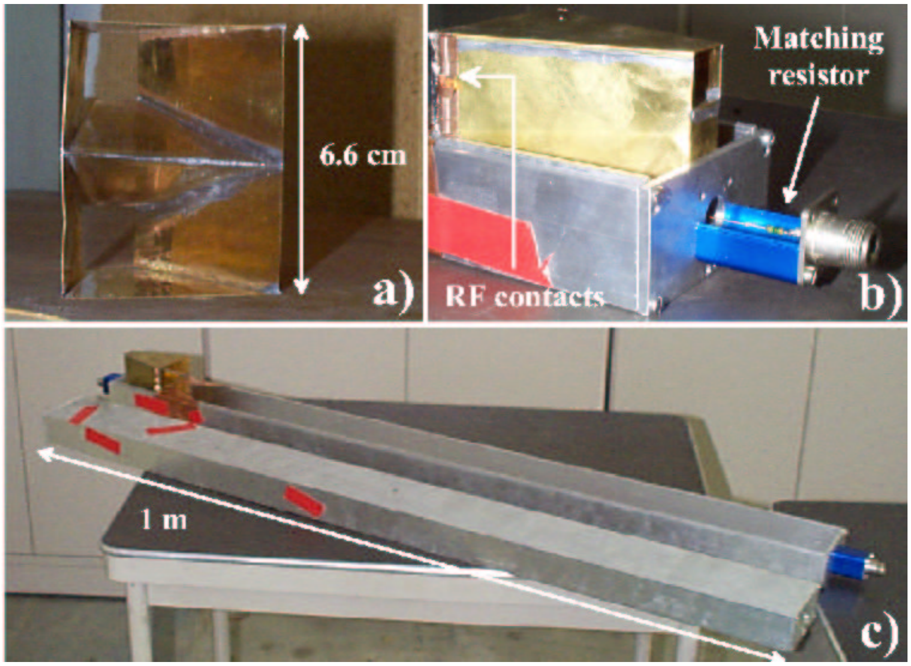

Figure 12: Bench measurement prototype. The taper is made of brass and proper RF contacts are soldered on it. A matching resistor joins each N-connector to the copper wire (0.4 mm of diameter). The tapered transition is inserted in aluminum box of one meter length. A “short” V-shaped metal sheet is soldered to the taper.

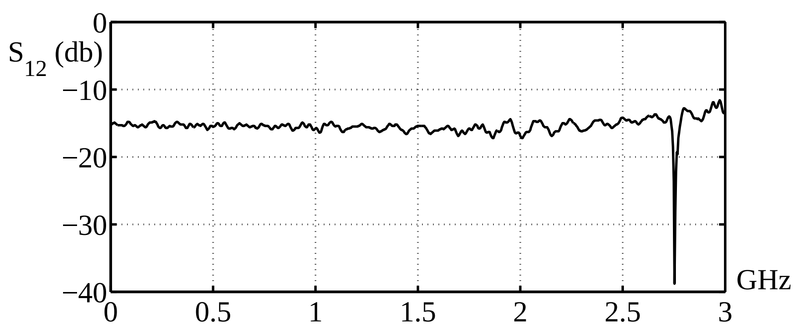

Figure 13: Transmission coefficient versus frequency for the tapered structure (no metal sheet). The strong resonant decrease in the transmission clearly indicates the presence of a trapped mode at 2.753 GHz.

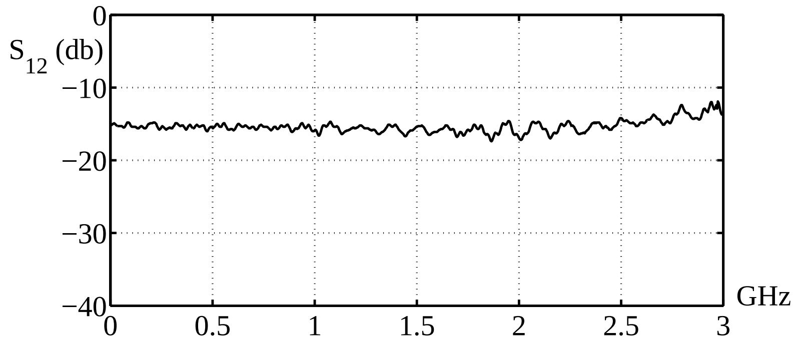

Figure 14: Transmission coefficient versus frequency for the tapered structure with a V-shaped metal sheet 20 cm long. The trapped mode related notch is so much reduced that it can not be seen in the measurements.

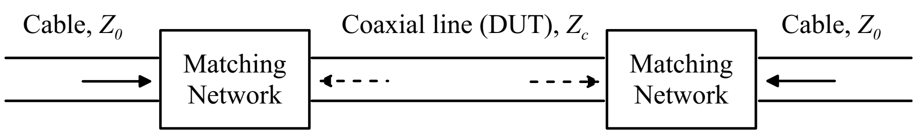

Figure 15: Schematic view of the bench measurement set-up. The Device Under Test (DUT) is the line in the middle with characteristic impedance Z_c. External cables, with impedance $Z_0 = 50\ \Omega$ connect the structure to the VNA and their terminations are assumed to be perfectly matched. The solid arrows represent waves going from the Z_0 transmission line to the coaxial line (Z_c) while the dashed lines represent waves in the opposite directions. An ideal matching network should avoid reflections for all those waves.

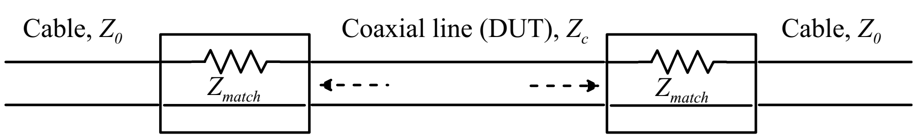

Figure 16: One resistor matching network. Only matching in one direction can be achieved. The resistor is chosen to avoid reflections only for waves going from the central coaxial line (Z_c) to the cables (Z_0), that is “internal matching”.

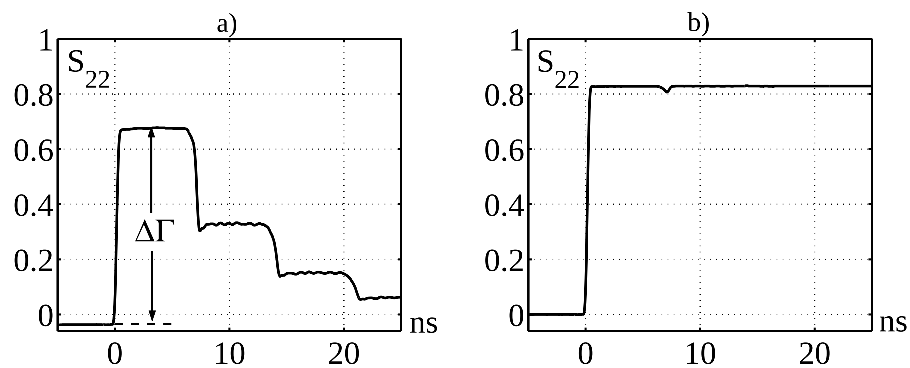

Figure 17: Reflection coefficient measurement in the time domain. The left plot is measured on the non-matched coaxial line while the right one is after including suitable matching resistors depending on the $\Delta\Gamma$ of the non-matched line ($\Delta\Gamma = 0.714$).