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*Large Hadron Collider Project*

**LHC Project Report 104**

# LHC Bellows Impedance Calculations

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## Abstract

To compensate for thermal expansion the LHC ring has to accommodate about 2500 bellows which, together with beam position monitors, are the main contributors to the LHC broad-band impedance budget. In order to reduce this impedance to an acceptable value the bellows have to be shielded. In this paper we compare different designs proposed for the bellows and calculate their transverse and longitudinal wakefields and impedances. Owing to the 3D geometry of the bellows, the code MAFIA was used for the wakefield calculations; when possible the MAFIA results were compared to those obtained with ABCI. The results presented in this paper indicate that the latest bellows design, in which shielding is provided by sprung fingers which can slide along the beam screen, has impedances smaller than those previously estimated according to a rather conservative scaling of SSC calculations and LEP measurements. Several failure modes, such as missing fingers and imperfect RF contact, have also been studied.

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Geneva, 21 April 1997

## 1 Introduction

To compensate for thermal expansion the LHC ring has to accommodate about 2500 bellows which, together with beam position monitors, are the main contributors to the LHC broad-band impedance budget [1]. The LHC bellows design is based on the LEP and the SSC bellows design [2]. Studies done for SSC bellows [3, 4] have shown that in order to reduce their impedances to acceptable values they have to be shielded; the same applies to LHC bellows.

There are some differences in the LHC bellows design compared to the SSC one – a major difference is the fact that the LHC beam screen has a race-track shape and, in order to provide even pressure on each finger touching the beam screen, it has been proposed to make a transition from race-track to circular shape. This transition will make an additional contribution to the bellows impedance and thus the effect of the transition length on the impedance should be investigated. There are a few other differences between LHC and SSC which should be mentioned: i) the average LHC beam-screen diameter is bigger, ii) the number of bellows in the LHC may be sightly less then in the SSC (2500 instead of 3000-4000 used in the SSC design). It should also be mentioned that the number of particles per bunch in the LHC is much larger than in the SSC ($1.05\times10^{11}$ compared to only $1.5\times10^{10}$ in the SSC).

A final design of the LHC bellows is not yet available and we try to study how different parameters (such as transition length, step size etc.) may affect the bellows impedances. The most recent design of the bellows is shown in Figs. 1-3.

## 2 Analytical Estimates

The fact that all transitions and discontinuities in the bellows are very small compared to the beam screen diameter makes it possible to estimate their impedances analytically. It should also be noted that since the r.m.s. bunch length in the LHC ($\sigma_\mathrm{l} \geq 7$ cm) is larger than the beam screen radius ($b \approx 2$ cm), the beam spectrum lays well below the cutoff frequency of the beam screen $f_\mathrm{cutoff} = 2.405\, c/2\pi b = 5.74$ GHz and therefore we are mostly interested in the low frequency limits of the impedances.

### 2.1 Impedance of a step

There will be always a small step (about 1 mm) in the area where the sliding fingers touch the beam screen; since this step will be small compared to the beam pipe radius, its contribution to the impedance can be estimated using analytical expressions for the low frequency impedances of small discontinuities.

For a small discontinuity, the imaginary part of the longitudinal impedance $Z_\mathrm{l}$ is given by the following analytic formula, which can be found in Ref. [5]:

$$Z_\mathrm{l}/n = -iZ_0 \frac{\omega_0}{c} \frac{(\alpha_{mag} + \alpha_{el})}{4\pi b^2}, \tag{1}$$

where $Z_0 = 120\,\pi\ \Omega$ and $\alpha_{el}$, $\alpha_{mag}$ are the electric and magnetic polarizabilities. The transverse impedance of an axially symmetric discontinuity can be obtained from the longitudinal one using the formula

$$Z_\mathrm{t} = \frac{2c}{b^2\omega_0} \frac{Z_\mathrm{l}}{n}. \tag{2}$$

The longitudinal impedance of a single step of size $h$ is given by [6]

$$Z_\mathrm{l}/n = -iZ_0 \frac{\omega_0}{c} \frac{h^2}{4\pi^2 b} \left[2\ln(2\pi b/h) + 1\right]. \tag{3}$$

The bellows may have one step (old designs with one set of fingers) or two steps (new design). The impedances of two well separated steps (i.e., of a long pill-box) are shown in Table 1. The average beta-function is $\beta_{\rm av} = 89$ m (see Table 4 in Appendix A for a list of several LHC parameters used in the calculations). The resistive part of the impedance of a small step is very small at the typical beam spectrum.

Table 1: Impedance contributions from two small steps in the bellows at the contact areas between fingers and beam screen.

| Step size | 1 mm | 2 mm | 3 mm | 4 mm |
|---|---|---|---|---|
| L, nH | 0.0340 | 0.118 | 0.243 | 0.402 |
| $Z_{\rm l}/n$, mΩ | 0.00240 | 0.00835 | 0.0172 | 0.028 |
| $Z_{\rm t}$, kΩ/m | 0.051 | 0.177 | 0.364 | 0.603 |
| 2500 × $Z_{\rm l}/n$, mΩ | 6.00 | 20.9 | 42.9 | 71.1 |
| 2500 × $Z_{\rm t} \times \beta_{\rm av}$, MΩ | 0.127 | 0.443 | 0.910 | 1.51 |

### 2.2 Impedance of a slot

The gaps between separate fingers as well as possible "missing fingers" have a very small size compared to the beam pipe radius and therefore their effect can be estimated by calculating low frequency impedances of a narrow slot [5].

The imaginary part of the longitudinal impedance of a slot is given by Eq. (1) and the transverse coupling impedances of a slot are given by analytical formulae which can be found in Ref. [5]

$$Z_{\rm t}(\omega) = -iZ_0 \frac{(\alpha_{mag} + \alpha_{el})}{\pi^2 b^4} \vec{a}_h \cos(\phi_h - \phi_b), \qquad (4)$$

where $\vec{a}_h$ is a unit vector in the direction of the hole and $\phi_h$, $\phi_b$ are azimuthal angles of the hole and the beam in the pipe cross-section.

The sum of electric and magnetic polarizabilities for a slot of width $w$ and length $l \gg w$ is

$$\alpha_{mag} + \alpha_{el} = w^3(0.1814 - 0.0344\, w/l). \qquad (5)$$

### 2.3 Power losses in bellows gaps

As it will be shown in this report, the impedance for different bellows design is well within the LHC impedance budget and the only effect which should be considered is the effect of power losses in the bellows and consequent heating. It is recommended that the total power loss in all bellows should not exceed 1 kW/ring [2], this number is much higher than the one used in the SSC design ($P < 190$ W).

The parasitic loss per bellows equals

$$P = k_{\rm l}\, e^2 N^2 M f_{\rm rev}, \qquad (6)$$

where $k_{\rm l}$ is the longitudinal loss factor, N the number of particles per bunch, M the number of bunches and $f_{\rm rev}$ is the revolution frequency. The loss factor is negligible in case of good RF contacts between bellows fingers and beam screen, but even a very small gap can contribute significantly to the power losses. The gap can be treated as a coaxial transmission line with inner radius $r_1 = b$ and outer radius $r_2 = b + \Delta$ and therefore the real part of the longitudinal impedance will be

$$Re(Z_l) = \frac{Z_0}{2\pi} \ln \frac{b+\Delta}{b} = \frac{Z_0}{2\pi} \frac{\Delta}{b} \tag{7}$$

where $b$ is the beam pipe radius.

Since $k_l$ can also be expressed as

$$k_l = \frac{1}{\pi} \int_0^{\infty} Re[Z(\omega)] e^{-\omega^2 \sigma_\tau} d\omega \tag{8}$$

where $\sigma_\tau = \sigma_z / c$, and $\sigma_z$ is the r.m.s. beam size, we finally get a formula for parasitic losses due to a gap $\Delta$

$$P = \frac{\Delta}{b} \frac{Z_0 c}{4\pi^{3/2} \sigma_z} N^2 e^2 M f_{\mathrm{rev}}. \tag{9}$$

Plugging typical LHC parameters at top energy (see Table 4 in Appendix A), we obtain the following expression for the power loss per gap:

$$P(\mathrm{W}) \simeq 30 \cdot \Delta(\mathrm{mm}). \tag{10}$$

Therefore, in order to have losses below 1 kW in 2500 bellows and taking into account that there are two sets of fingers, the maximum allowed gap is about $\Delta = 0.006$ mm.

### 2.4 Power losses in other discontinuities

Since the frequency spectrum of the LHC bunch is concentrated in a region well below cutoff frequency of the pipe, we can use the following formula from Ref. [5]:

$$Re[Z(\omega)] = Z_0 \left(\frac{\omega}{c}\right)^4 \frac{(\alpha_{mag}^2 + \alpha_{el}^2)}{24\pi^3 b^2}, \tag{11}$$

i.e., the resistive part of the impedance is very small at the frequencies below the cutoff and the power losses from all the steps in the bellows will be less than a few watts per ring and can be disregarded. Power losses in the gaps ($< 1$ mm) between fingers are also found to be small.

It is also possible to estimate power losses in the case of "missing fingers". The situation when the RF contact is lost for all fingers in a single bellows is equivalent to the "gap" which was considered in the previous subsection. From Eq. (10) we see that, if we assume $\Delta = 1$ mm, the power losses in a single bellows may be 30 W! However, it is unlikely that the RF contact will be lost at all fingers simultaneously. It is more likely that only one or two fingers break at the same time, therefore we need to estimate the power losses due to a few missing fingers. If the power losses due to the "missing" fingers will be higher than the maximum power of the cooling power in the region near the the broken contact, this may cause overheating of neighbouring fingers and their subsequent breakup.

We can approximate the missing fingers as a long slot. The following formula for the low frequency resistive part of the longitudinal impedance for a long slot is given in Ref. [5]:

$$Re[Z(\omega)] = \frac{Z_0}{6912\,\pi} \left(\frac{\omega w}{c}\right)^4 \frac{l^2}{b^2}, \tag{12}$$

where $w$ is the slot's width and $l$ is its length. Power losses due to a missing finger can therefore be calculated using Eq. (6), where the loss factor is given by Eq. (8) and $Re[Z(\omega)]$ is given by the equation above. Our estimates show that these losses are negligible.

## 3 Numerical Results

Due to the distinctive 3D geometry of the proposed LHC bellows designs and in order to be able to compare the results for different bellows, it has been decided to use the MAFIA T3 module (3D time domain) for all the calculations. Unfortunately, due to computing limitations, the minimum mesh size we were able to use in our calculations was only 0.5 mm in the transverse planes and 1 mm in the longitudinal direction, i.e., memory limitations were our major constraint since the CPU time on the 200 MHz DEC Alpha station was only about 1-2 hours for a typical geometry.

The impedances are defined in terms of the wake-functions generated by a point charge

$$Z_{\mathrm{l}} = \int_0^\infty W_{\mathrm{l}}(t) e^{i\omega t}, \tag{13}$$

$$i\, Z_{\mathrm{t}} = \int_0^\infty W_{\mathrm{t}}(t) e^{i\omega t}. \tag{14}$$

However, in the simulations we can only use a bunch with a finite bunch length. In our simulations we used MAFIA T3 to calculate the wakefields generated by a test Gaussian bunch with charge Q=1 and r.m.s. length $\sigma_{\mathrm{z}} = 1$ cm, displaced by 5 mm from the centre of the beam pipe in both vertical and horizontal planes and travelling with the speed of light. The wakefields have been calculated with the step 1 mm and were truncated at 52 cm.

FFT of the wakefield has been used to obtain the effective impedance $\hat{Z}(\omega)$ seen by the bunch, which is related to the actual impedance $Z(\omega)$ seen by the point charge by

$$\hat{Z}(\omega) = Z(\omega)\, e^{\frac{-\omega^2 \sigma_\tau^2}{2}}. \tag{15}$$

Therefore the results become meaningless if $\omega^2 \sigma_\tau^2 \gg 1$. The bunch length used in the simulations ($\sigma_{\mathrm{l}} = 1$ cm) allowed us to obtain the impedance up to 10-12 GHz (about twice the LHC beam screen cutoff frequency $f_{\mathrm{cutoff}} = 5.74$ GHz). On the graphs the impedance is shown up to 16 GHz, together with the spectrum of the $\sigma_{\mathrm{z}} = 1$ cm bunch. Unfortunately, since the displacement of the beam in the transverse direction was only 10 mesh points, one should expect additional errors (at least 15-20%) in the transverse impedances at low frequencies. These errors will be even bigger at higher frequencies.

ABCI and MAFIA have been applied to the same axisymmetrical geometry (long pill-box on the beam pipe with radius $b = 18$ mm, step $\Delta = 4$ mm and length $l = 100$ mm) shown in Fig. 4. MAFIA generated wakefields and the impedances calculated from them are shown in Figs. 5–11, while ABCI results are in Figs. 12–18. The difference between ABCI and MAFIA T3 for this simple geometry was less then 10% at frequencies below the cutoff frequency. Also the low frequency limits found from both programs agree very well with the analytical estimates obtained using the formulae of Refs. [5] and [6].

The results for the "inner bellows" structure (see Fig. 19) are shown in Figs. 20–28. The structure consists of 12 corrugations with 4 mm depth and 8 mm period, on a beam pipe with radius $b = 18$ mm. The impedances of this structure were up to 5 times higher than the impedances of the shielded bellows (see results below) and therefore this type of shielding cannot be used in the LHC (this design has been also rejected for the SSC). The impedance of this structure can be reduced by making the period of the corrugations smaller, however in order to have the impedance within the allowed budget we may need to have them in the order of 1 mm in the cold (expanded) state.

### 3.1 Beam Pipe Transition

In this section we study the effect of the transition length from the race-track shape to a circle, which is made in order to have the same pressure on each of the sliding fingers.

Let us first consider the model which consists of two beam pipes connected by a matching cylinder (see Figs. 29 and 39). This model does not include other discontinuities, such as a small step of about 1 mm which is unavoidable at the point of contact between fingers and beam pipe and which will be considered in the following subsection. Four different transition lengths have been studied: $d = 0$ (see Fig. 29), $d = 10$ mm (see Fig. 39), $d = 20$ mm and $d = 35$ mm. The MAFIA generated wakefields and the corresponding impedances in the case of sharp transition, $d = 0$ (Fig. 29), are shown in Figs. 30–38, while the results for a transition length $d = 10$ mm (Fig. 39) are shown in Figs. 40–48. The low frequency impedances obtained from the results of the simulations are shown in Table 2. It is interesting to note that the transverse impedances in horizontal and vertical planes are not only different, but have also different signs. Both transverse and longitudinal impedances decrease sharply if the transition length changes from 0 to 10 mm, and only slightly if it increases from 10 to 35 mm.

Table 2: Low frequency impedances for different transition lengths.

| Transition | 0 mm | 10 mm | 20 mm | 35 mm |
|---|---|---|---|---|
| $Z_l/n$, m$\Omega$ | 0.0072 | 0.0035 | 0.0034 | 0.0028 |
| $Z_{\rm t}(v)$, k$\Omega$/m | 0.413 | 0.205 | 0.199 | 0.121 |
| $Z_{\rm t}(h)$, k$\Omega$/m | -0.276 | -0.138 | -0.129 | -0.079 |

### 3.2 More realistic model: transition + step

In this section we will calculate the impedances of a model bellows which includes smooth transitions and two steps. We have also simulated the effect of "missing fingers". Using arguments from the previous subsection, the transition length was set to 10 mm and we calculated the wake fields and the impedances for two different values of the steps, namely 1 mm and 2 mm (keeping in mind that though the beam screen is only 1 mm thick some extra step may be required to allow a good RF contact with the fingers). The MAFIA generated wakefields and the impedances calculated from them for the case of a transition length $d = 10$ mm and a step $\Delta = 1$ mm (Fig. 49) are shown in Figs. 50–58.

A "missing finger" was also simulated as a long narrow slot. The width of the slot used in the simulations was 6 mm (which is in fact equivalent to 2 missing fingers in the same place) though, as one can see from Table 3, the effect of this slot on the overall impedance is very small. The low frequency impedances for the structures considered are presented in Table 3.

As one can see from Table 3, the longitudinal impedance of the bellows with step $\Delta = 2$ mm is only 0.0134 m$\Omega$, which results in $Z_{\rm l}/n = 33.5$ m$\Omega$ for 2500 bellows (i.e., less than half the value of 80 m$\Omega$ previously allocated for bellows in the LHC impedance budget [1]) and $Z \times \beta_{\rm av} = 0.910$ M$\Omega$ also smaller than the value originally used in Ref. [1].

Table 3: Low frequency impedances of the model bellows with smooth transitions of 10 mm and two steps, for different step sizes and including the case of a missing finger (m.f.).

| Step size | 0 mm | 1 mm | 1 mm + m.f. | 2 mm |
|---|---|---|---|---|
| $Z_l/n$, m$\Omega$ | 0.0035 | 0.0061 | 0.0062 | 0.0134 |
| $Z_t(v)$, k$\Omega$/m | 0.205 | 0.251 | 0.249 | 0.344 |
| $Z_t(h)$, k$\Omega$/m | -0.138 | -0.088 | -0.094 | -0.007 |

## 4 Conclusion

The calculated impedances of the LHC bellows were found to be smaller than the values used in Ref. [1] (based on a rather conservative scaling of SSC calculations and LEP measurements), in which up to 25% of the low frequency impedance budget was allocated to bellows. Even the most pessimistic model of the bellows, approximated by a 4 mm pill-box (see Table 1) is within the proposed LHC impedance budget [1]; it is more likely, however, that the low frequency impedance will be even less than this pessimistic estimate (see Table 3).

It has been found that one of the most significant factors contributing to the impedance of the bellows is the size of the step at the point of contact between sliding fingers and beam screen. Therefore additional care should be taken to make this step as small as possible, but retaining at the same time a good RF contact between the fingers and the beam screen, in order to avoid parasitic power losses in the bellows. The gap between the sliding contacts and the beam screen should be less than 0.006 mm in order to keep the power losses in the bellows $P < 1$ kW.

The results obtained with MAFIA were found to be in reasonably good agreement with results obtained with ABCI (for 2D test structures) and with analytical estimates obtained using formulae from Ref. [6] and approximating the bellows geometry by axially symmetric structures with some average radii. In some structures considered in this report the transverse wakefields and impedances in the vertical and horizontal planes are not only different, but have also different signs (i.e., focusing in one plane and defocusing in the other). The effect of the gaps between fingers is found to be negligible compared to the effect of steps and transitions.

More up to date results can be found on the World Wide Web, at the URLs `http://wwwslap.cern.ch/collective/misha/` and `http://decu10.triumf.ca:8080/lhc/`. In addition to the results presented in this paper, these WEB pages also contain the raw wakefield data as well as the impedances calculated for different LHC elements (strip-line BPM's, collimators, etc.). They also provide links to scripts which can be used to calculate low frequency impedances of small discontinuities using analytical expressions derived by Zotter, Gluckstern, Heifets, Kurennoy and Stupakov.

**Acknowledgements**

We would like to thank Alastair Mathewson and Ray Veness, of the LHC Vacuum Group, for useful discussions about the LHC bellows design and for providing us with their latest version.

## References


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## Appendix A: List of LHC Parameters

Some of the LHC parameters used in the calculations are given in Table 4.

Table 4: Some LHC parameters used in the calculations.

| Parameters | Notation | Values |
|---|---|---|
| Energy | E | 400 GeV / 7 TeV |
| Circumference | $2\pi R$ | 26.659 km |
| Revolution frequency | $f_{\rm rev}$ | 11.25 kHz |
| RF frequency | $f_{\rm rf}$ | 400.8 MHz |
| Harmonic number | $h_{\rm rf}$ | 35640 |
| Number of bunches | $M$ | 2835 |
| Protons per bunch | $N$ | $1.1\times10^{11}$ |
| Beam pipe radius | $b$ | 20 mm |
| Beta function | $\beta_{\rm av}$ | 89 m |
| r.m.s. bunch length | $\sigma_{\rm l}$ | 11/7.5 cm |

## Appendix B: Example of command file for MAFIA module M

```
! rm m29.drc
#file name=m29 type=m stat=new act=open ex
#mesh
  zmesh 0 s180 0.180
  xmesh -0.035 s13 -0.022 s12 -0.016 s32 0.016 s12 0.022 s13 0.035
  ymesh -0.035 s70 0.035 ex
#brick
  mat=1
  volume -0.035 0.035 -0.035 0.035 0 0.180 ex
#ccylinder
```

```
  mat=0
  orientation=z
  center=0,0
  radius=0.022
  part=full
  fillmode=diagonal
  range=0.0, 0.180 ex
  radius=0.024
  range=0.060, 0.120 ex
#brick
  mat=1
  volume -0.025 -0.018 -0.025 0.025 0 0.040 ex
  volume  0.018  0.025 -0.025 0.025 0 0.040 ex
  volume -0.025 -0.018 -0.025 0.025 0.140 0.180 ex
  volume  0.018  0.025 -0.025 0.025 0.140 0.180 ex
#cylinder
  mat=2
  orientation=y
  fillmode=diagonal
  range=-0.025, 0.025
  point=0.040, 0.022
    line
  point=0.050, 0.022
    line
  point=0.040, 0.018
    line
  point=0.040, 0.022 ex
$
  point=0.140, -0.022
    line
  point=0.130, -0.022
    line
  point=0.140, -0.018
    line
  point=0.140, -0.022 ex
$
  point=0.040, -0.022
    line
  point=0.040, -0.018
    line
  point=0.050, -0.022
    line
  point=0.040, -0.022 ex
$
  point=0.140, 0.022
    line
  point=0.140, 0.018
    line
```

```
  point=0.130, 0.022
    line
  point=0.140, 0.022 ex
$
#washer
  mat=4
  center=0, 0
  inn=0.023
  out=0.060
  part=full
  orient=z
  range=0.005, 0.175 ex
$
  mat=0
  inn=0.023
  out=0.033 ex
$
  mat=3
  inn=0.023
  out=0.025
  range=0.050, 0.130 ex
#brick
  mat=0
  volume -0.003 0.003 -0.025 0.0 0.050 0.130 ex
#washer
  mat=1
  center=0, 0
  inn=0.022
  out=0.023
  part=full
  orient=z
  range=0.120, 0.130 ex
  range=0.050, 0.060 ex
#file type=m stat=old act=close ex
quit
```

**Appendix C: Command file for MAFIA T3 module**

```
&mfile mtmp
define xoff 0.005
define yoff 0.005
define beamsig 0.010
#boundary
xboundary=elec,elec
yboundary=elec,elec
zboundary=wave,wave
#material
mat=0 type=normal epsilon=1 mu=1 cond=0
mat=1 type=electric
```

```
mat=2 type=electric
mat=3 type=electric
mat=4 type=electric
#time
tstep=@real02
tend="(0.180+0.52)/@c0"
#beam xpos="xoff" ypos="yoff"
beamdirection=zaxis
beta=1 bunch=gaussian sigma="beamsig" isigma=5 charge=1
#time
nend="@integer03+@integer05"
#monitor
type=wake
window=signal
slow=0 shigh=0.52
xp="xoff" yp="yoff"
symbol=wp component z ex
symbol=wpx component x ex
symbol=wpy component y ex
#control
mapstep=1 dumpsave=no usebuffer=yes
ex
nomess noprompt
&pfile waketmp
echo ' 0.001 0.010 5 512 0.005 0.005 '
for i=1,512
  echo "wp(i)", "wpx(i)", "wpy(i)"
endfor
#file act=close type=p ex
mess prompt
quit
```

**Appendix D: Command file for MAFIA P module**

The same file has been used to produce pictures of all configurations; this file can also be found on the WWW: `http://decu10.triumf.ca:8080/lhc/bellows.html`

```
&mfile mtmp
#volumeplot
box yes
material all
view 45 70 90
cell=no
model=solid
cutterbody=-0.025, 0.025, 0, 0.025, 0.005, 0.180
open col ex
#file type=m stat=old act=close ex
```

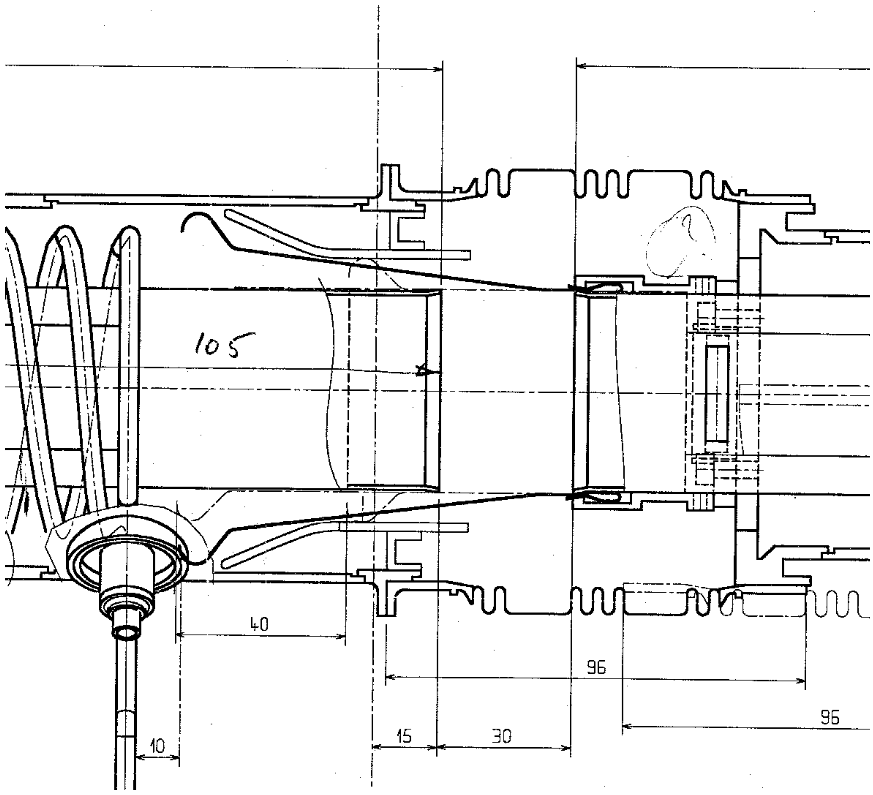


Figure 1: Most recent LHC bellows design (November 1996).

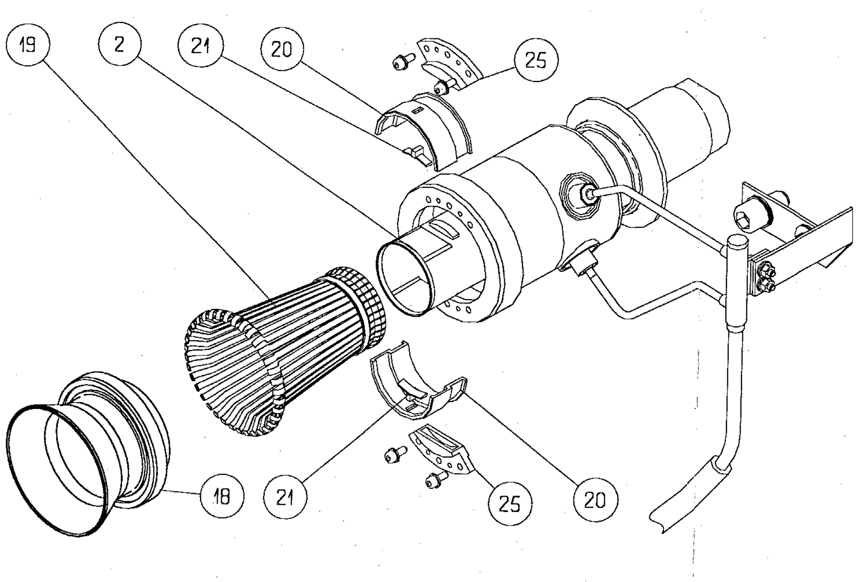


Figure 2: 3D drawing of the bellows assembly.

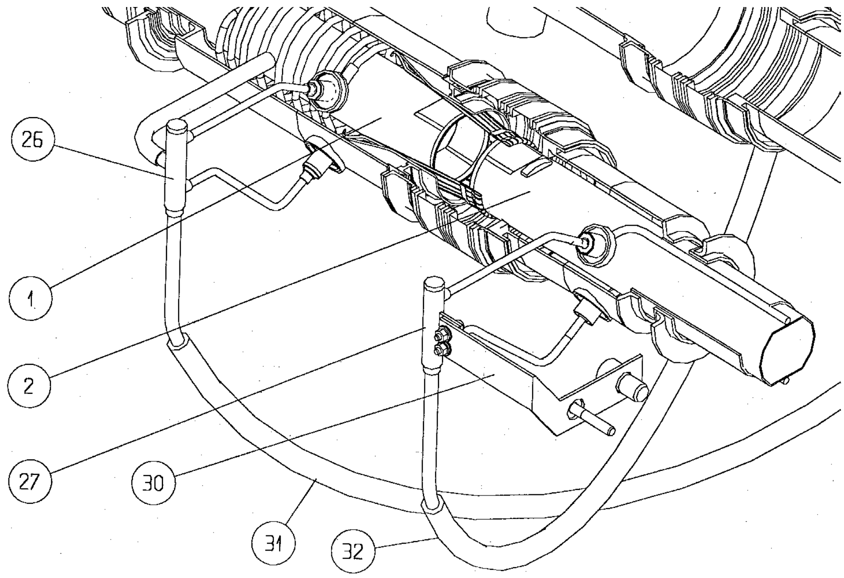


Figure 3: 3D drawing of the most recent LHC bellows design.

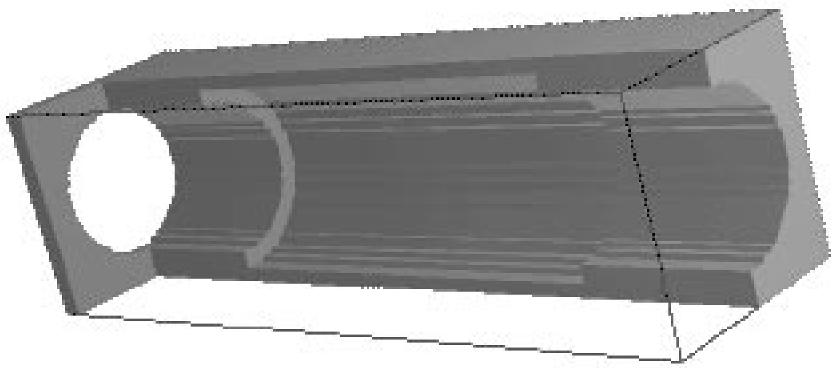

Figure 4: Model used in the calculations – simple pilbox.

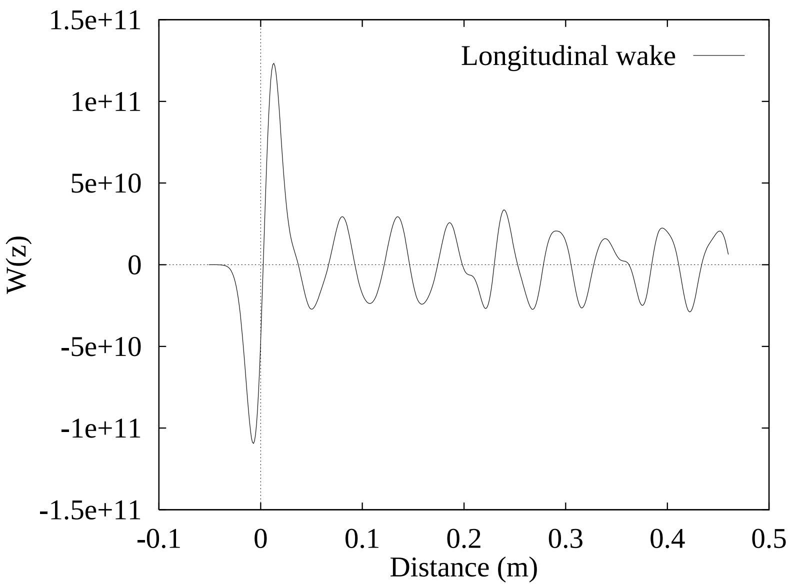


Figure 5: Longitudinal wakefield.

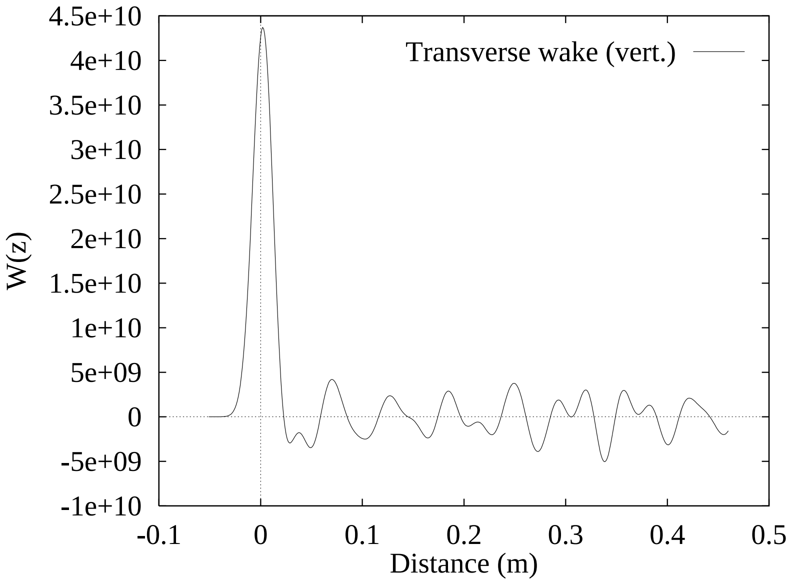


Figure 6: Transverse wakefield (vertical plane).

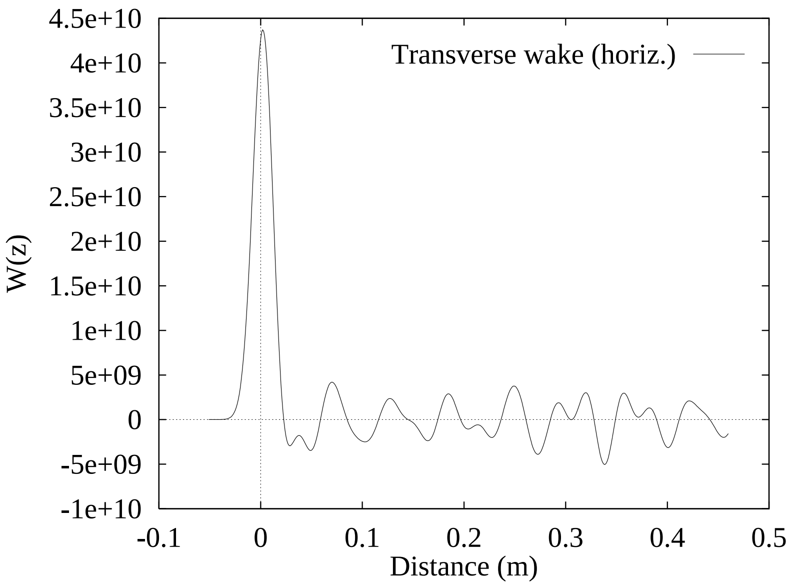


Figure 7: Transverse wakefield (horizontal plane).

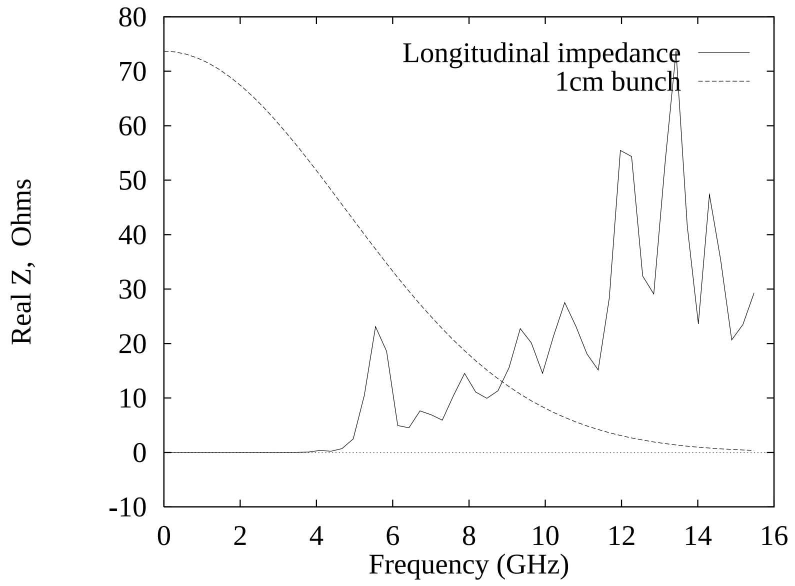


Figure 8: Real part of the longitudinal impedance.

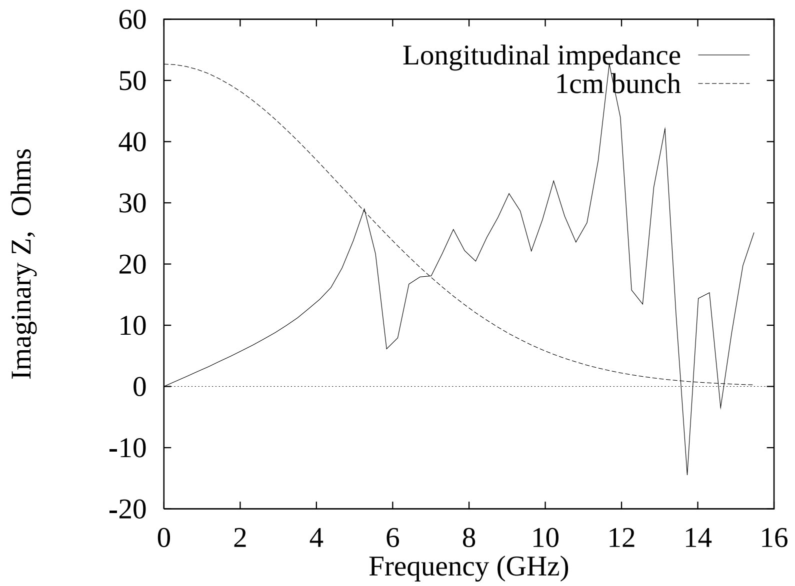


Figure 9: Imaginary part of the longitudinal impedance.

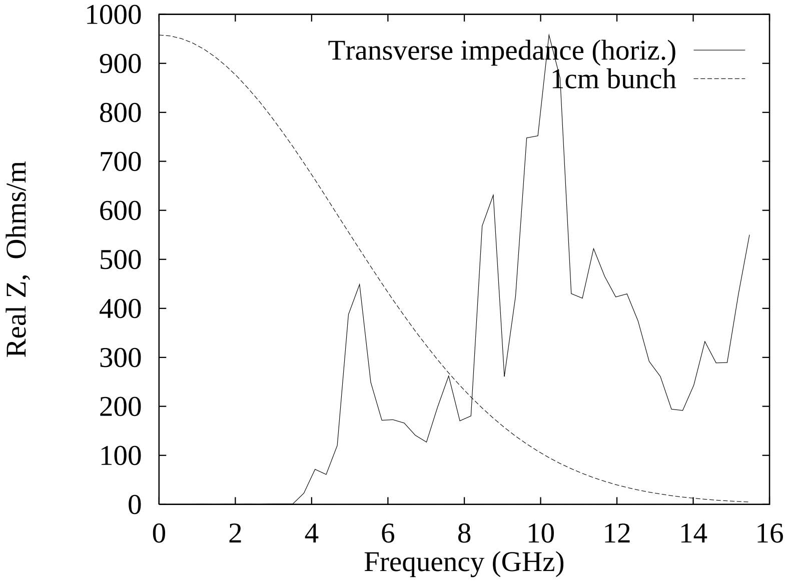


Figure 10: Real part of the transverse impedance.

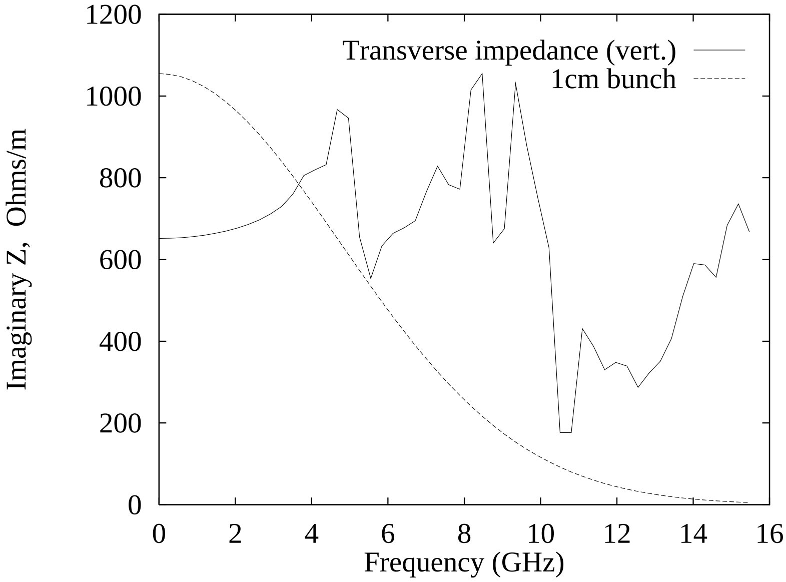


Figure 11: Imaginary part of the transverse impedance.

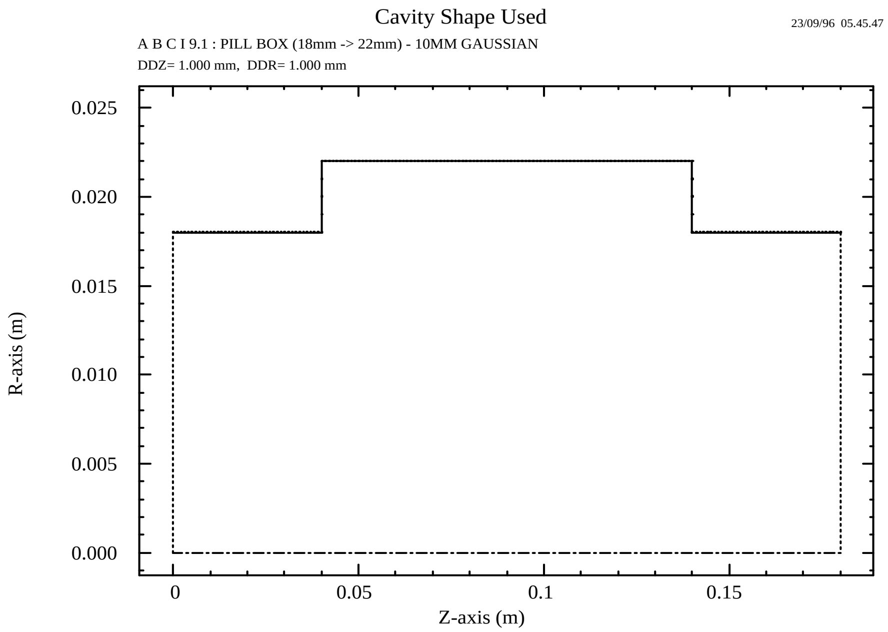


Figure 12: Geometry used in ABCI calculations.

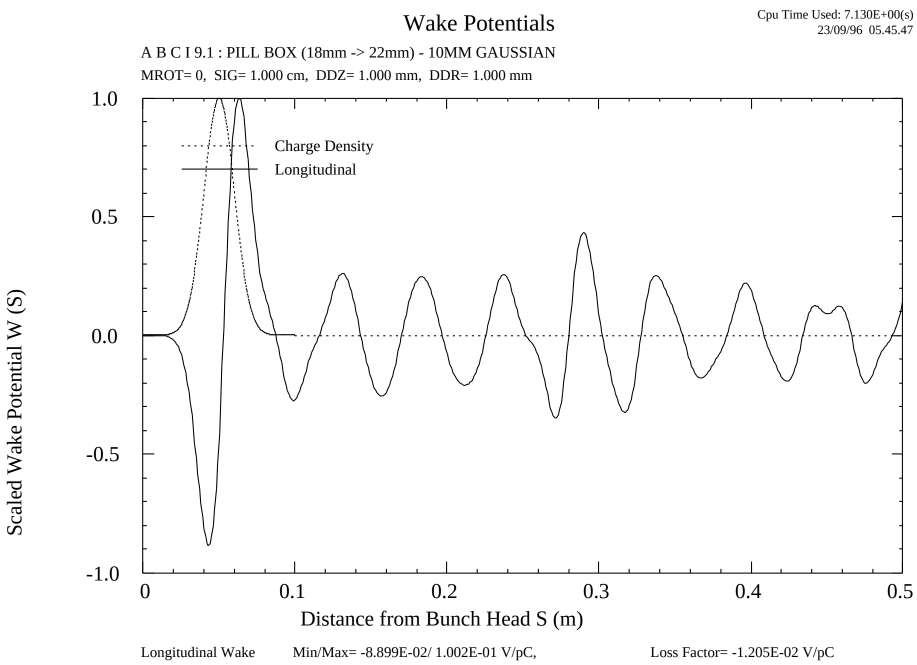


Figure 13: Longitudinal wakefield.

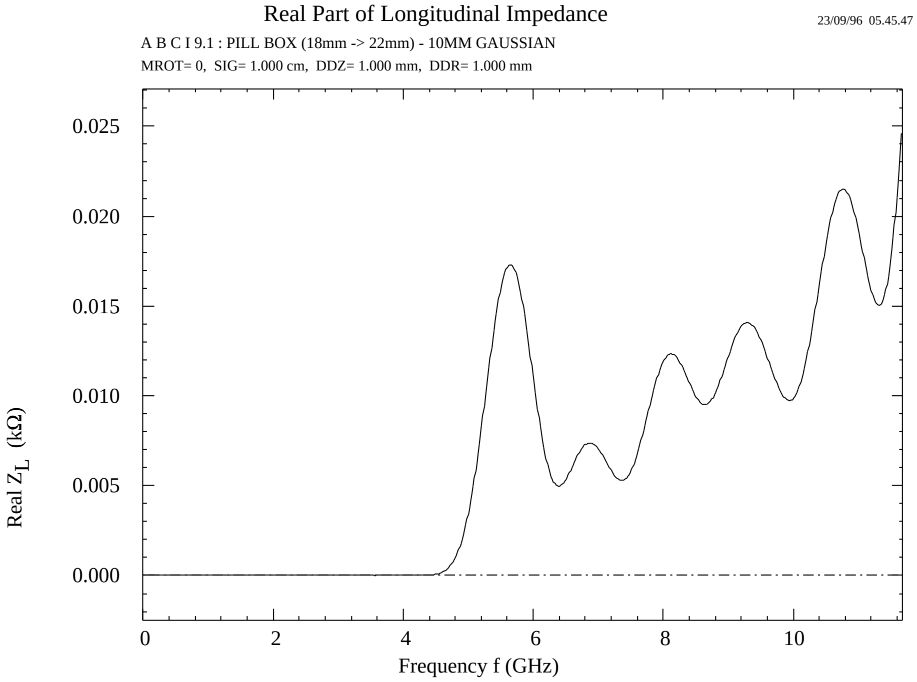


Figure 14: Real part of the longitudinal impedance.

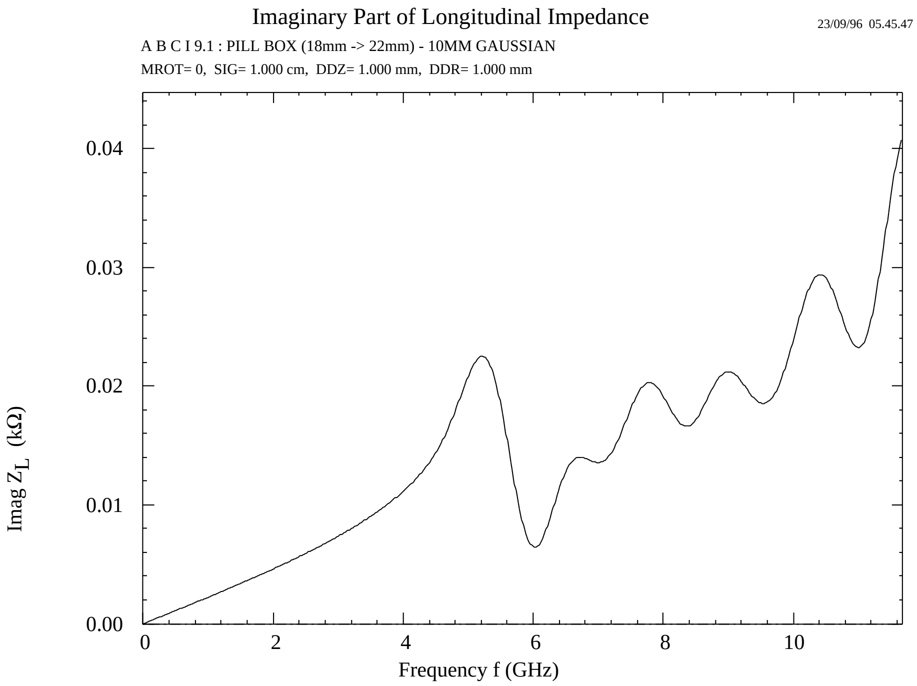


Figure 15: Imaginary part of the longitudinal impedance.

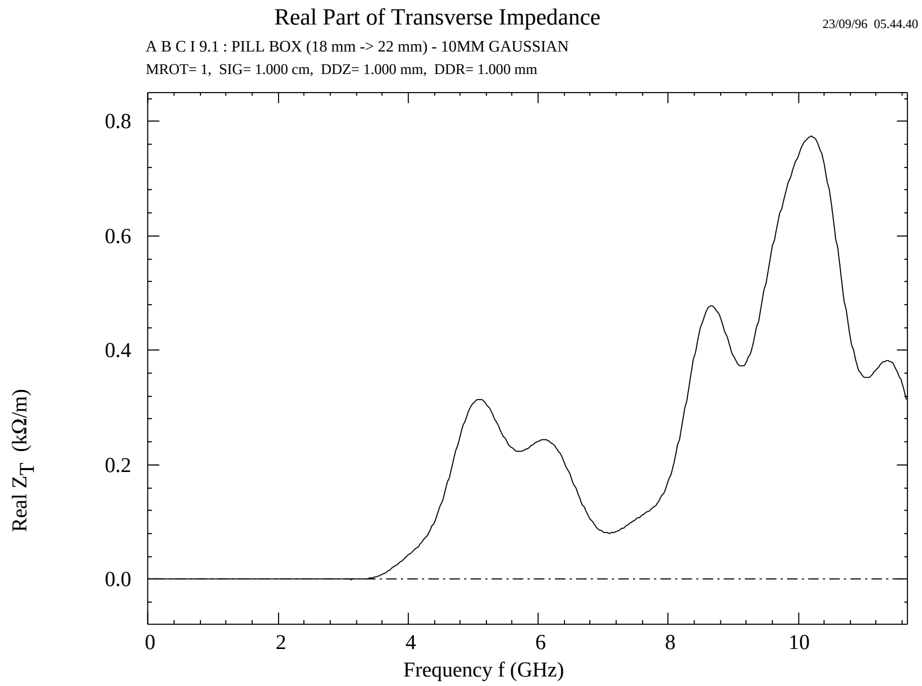


Figure 16: Real part of the transverse impedance.

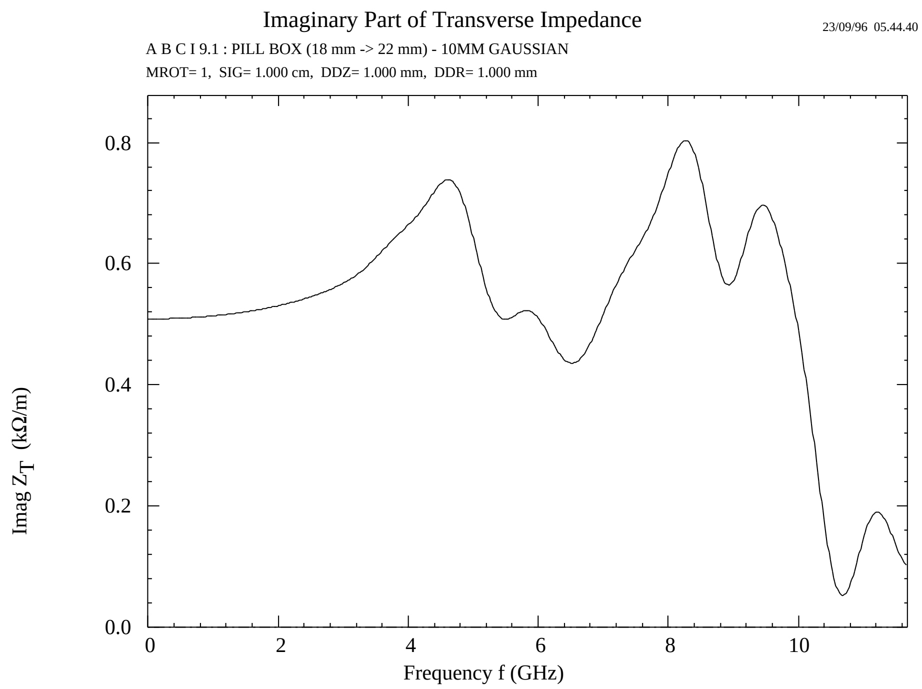


Figure 17: Imaginary part of the transverse impedance.

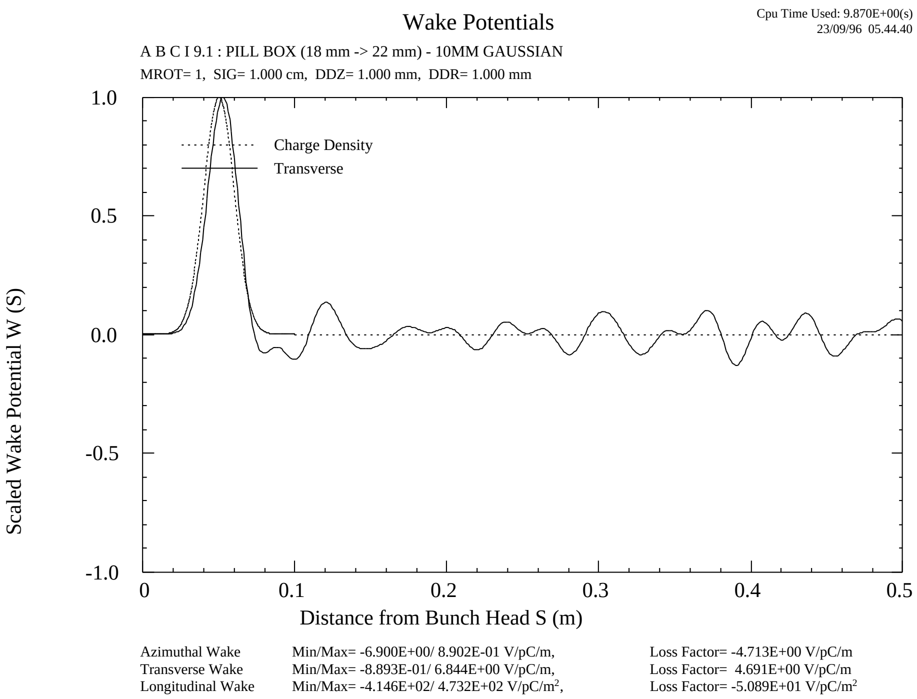


Figure 18: Transverse wakefield.

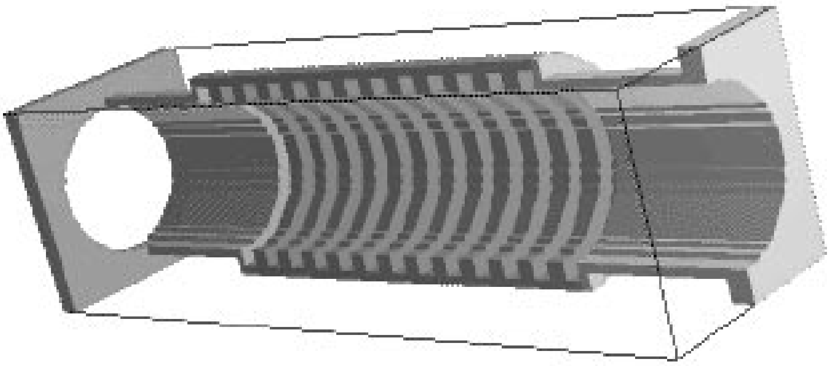

Figure 19: Series of 12 corrugations with 8 mm period.

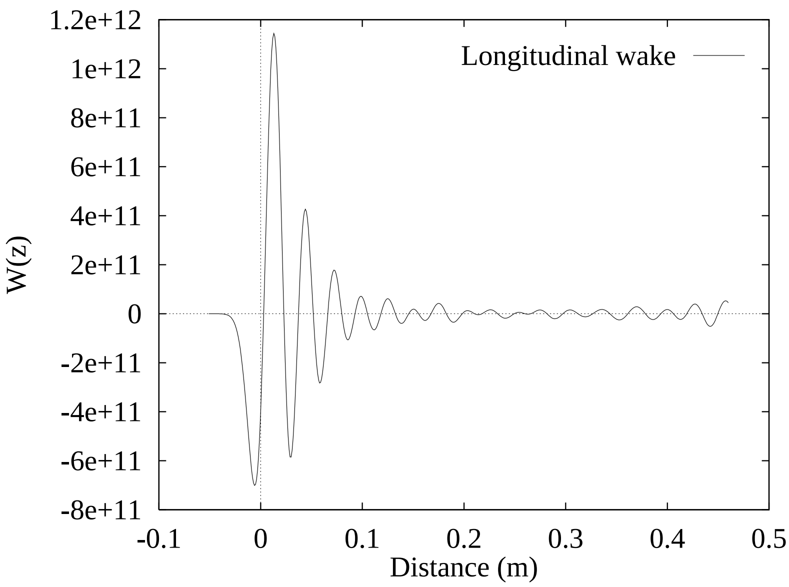


Figure 20: Longitudinal wakefield.

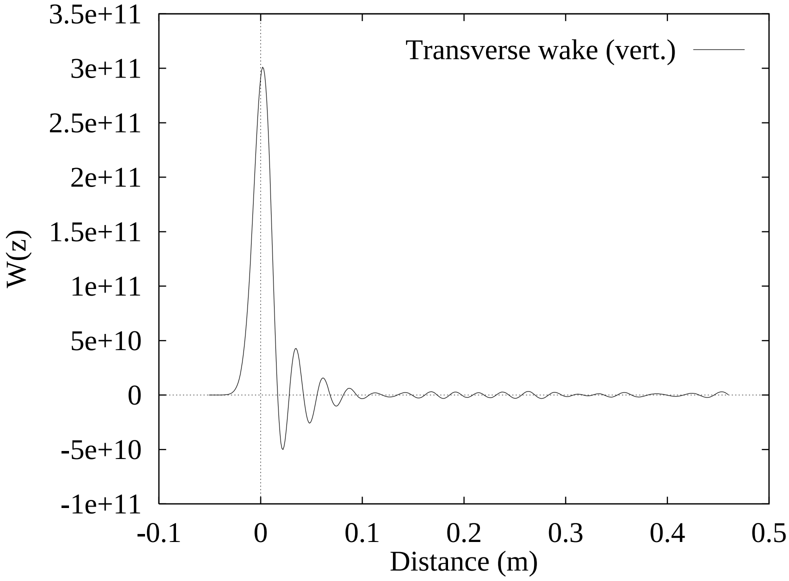


Figure 21: Transverse wakefield (vertical plane).

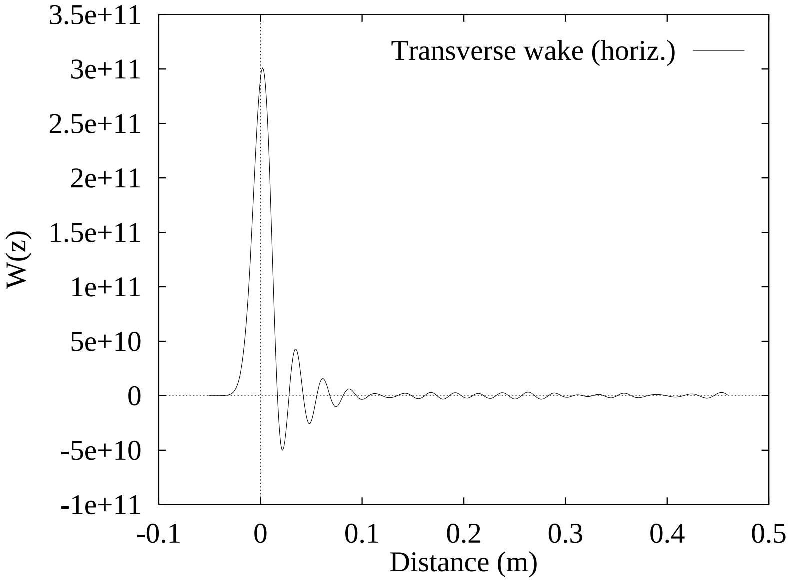


Figure 22: Transverse wakefield (horizontal plane).

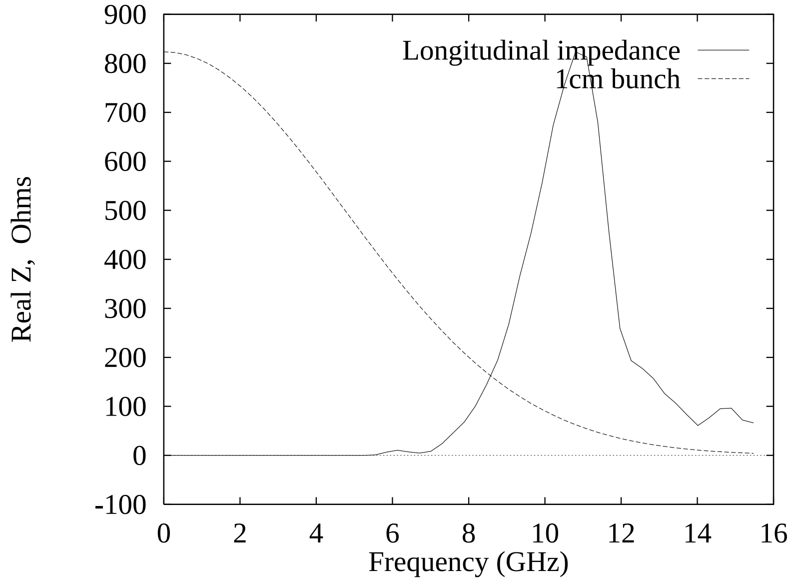


Figure 23: Real part of the longitudinal impedance.

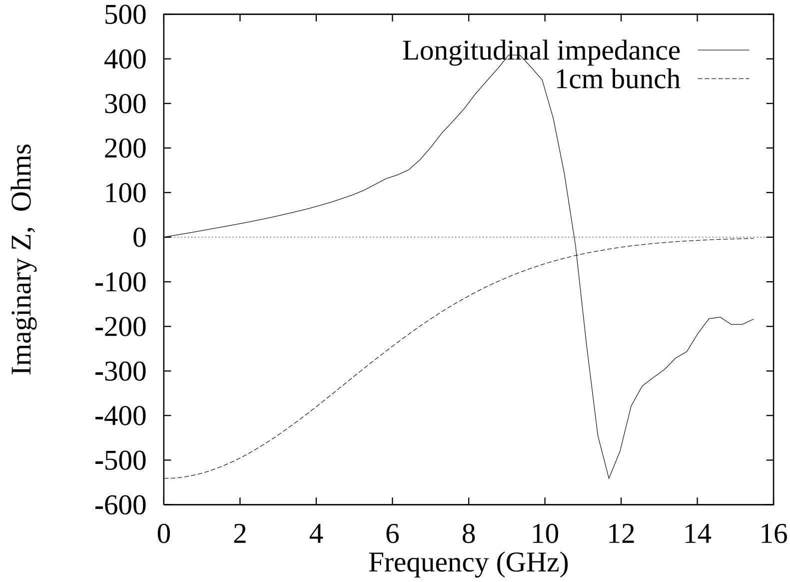


Figure 24: Imaginary part of the longitudinal impedance.

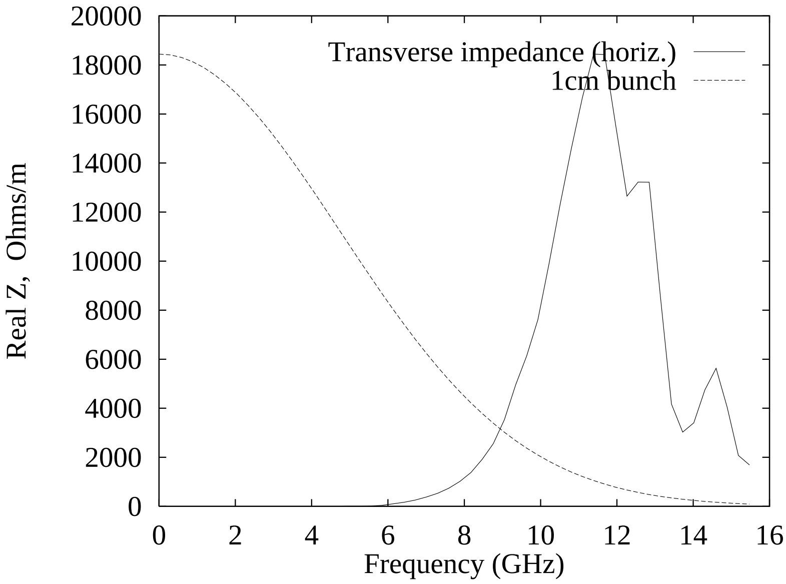


Figure 25: Real part of the transverse impedance (vertical plane)

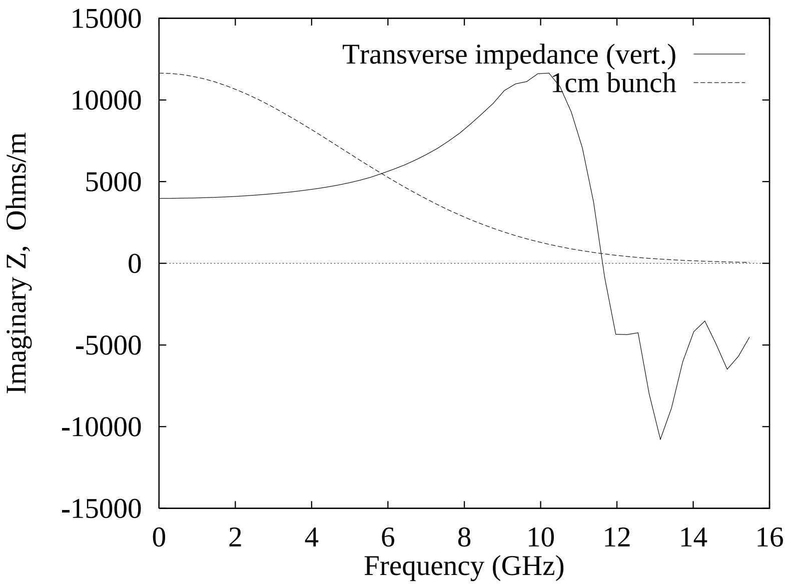


Figure 26: Imaginary part of the transverse impedance (vertical plane).

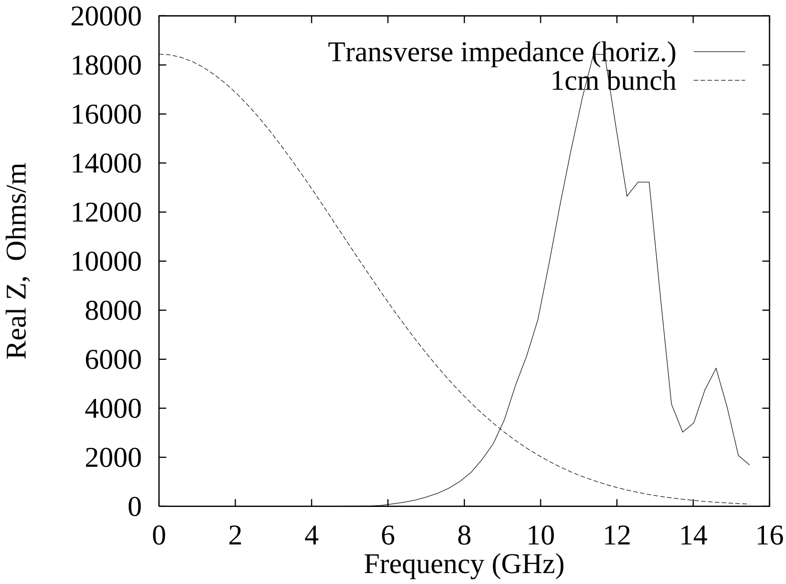


Figure 27: Real part of the transverse impedance (horizontal plane).

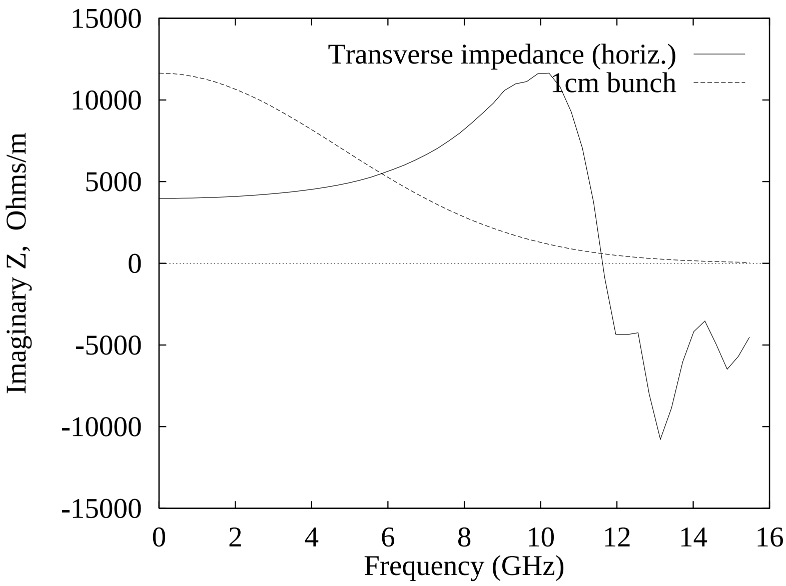


Figure 28: Imaginary part of the transverse impedance (horizontal plane).

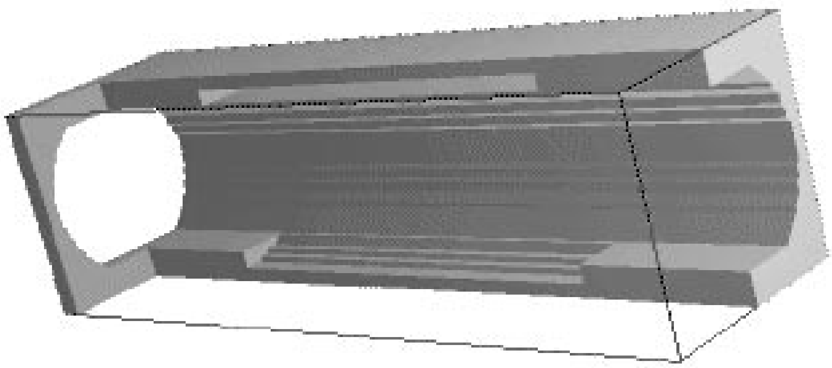

Figure 29: Sharp transition from the beam screen shape to a matched cylinder.

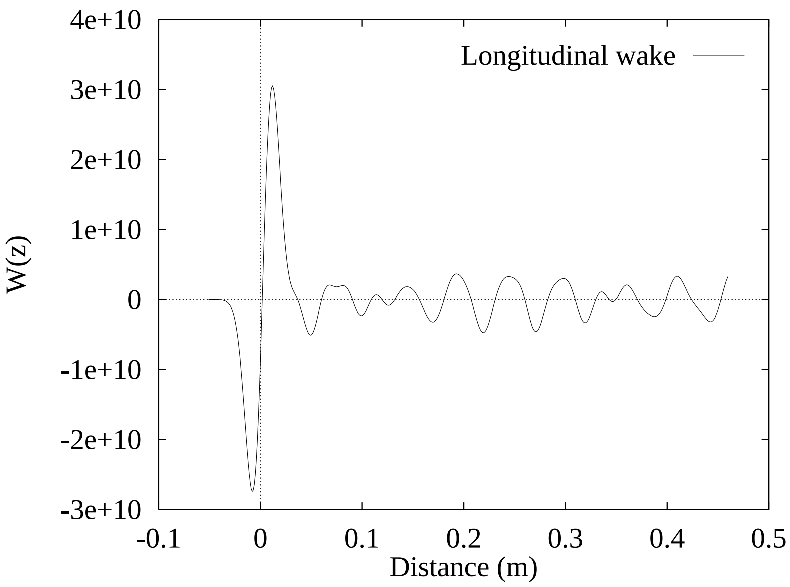


Figure 30: Longitudinal wakefield.

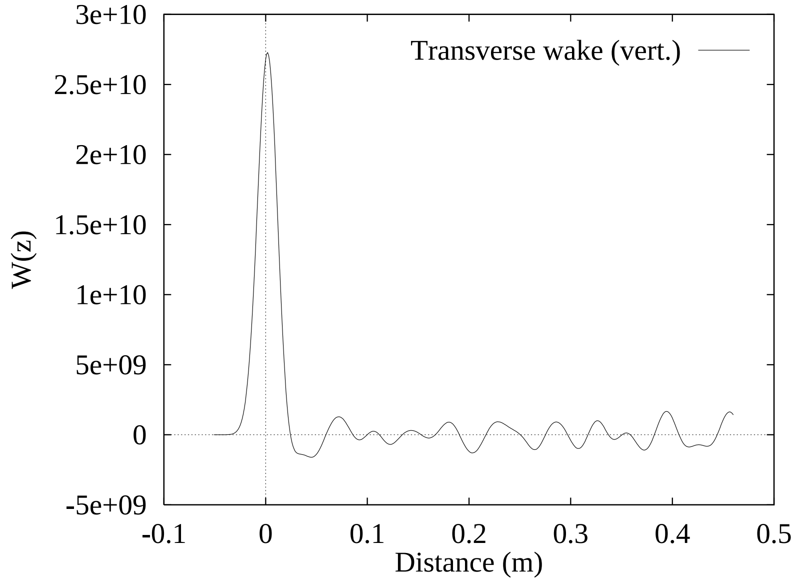


Figure 31: Transverse wakefield (vertical plane).

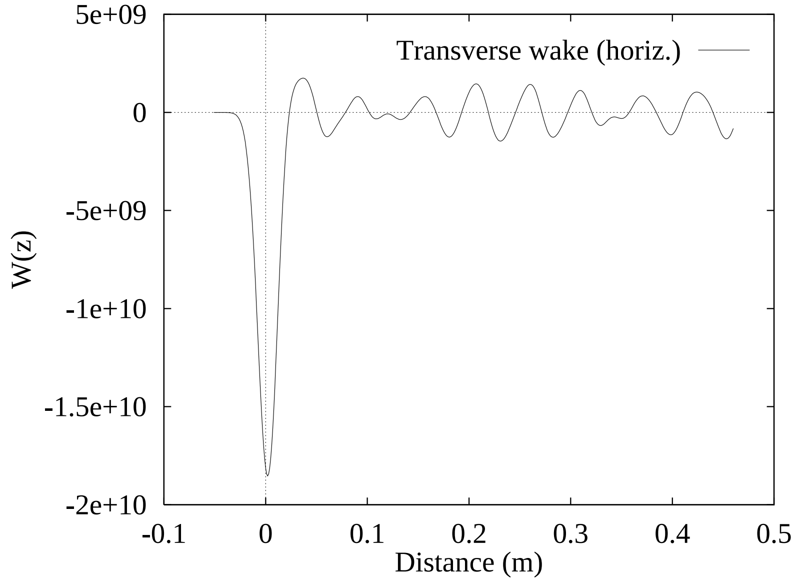


Figure 32: Transverse wakefield (horizontal plane).

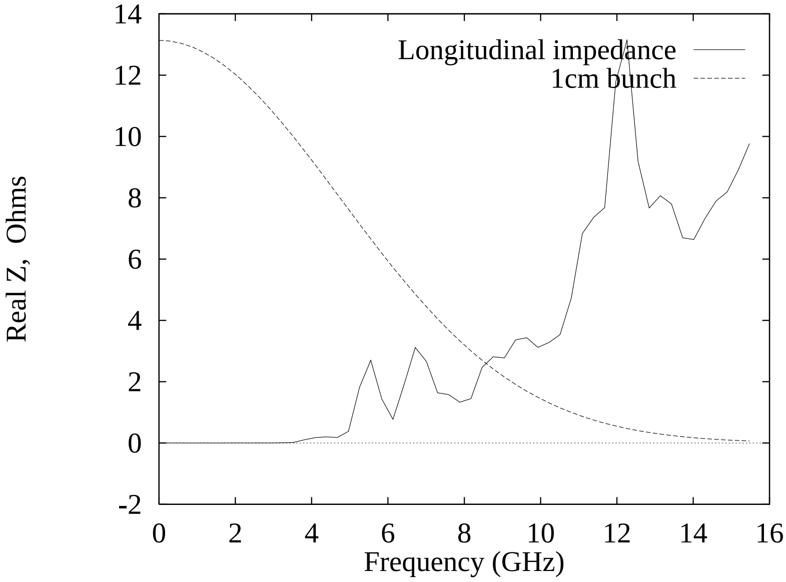


Figure 33: Real part of the longitudinal impedance.

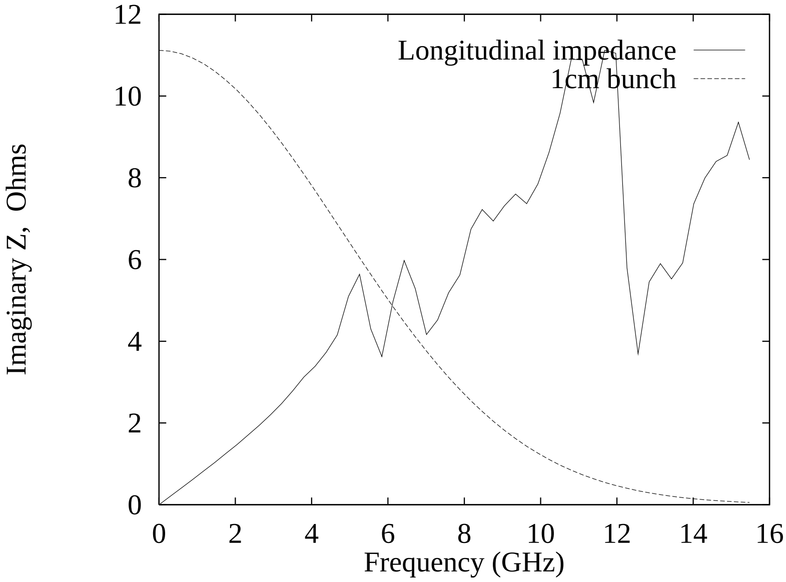


Figure 34: Imaginary part of the longitudinal impedance.

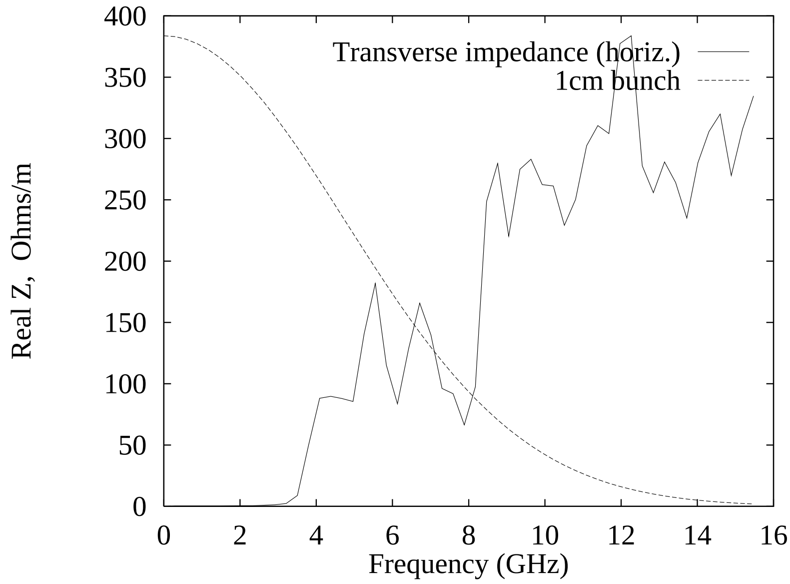


Figure 35: Real part of the transverse impedance (vertical plane).

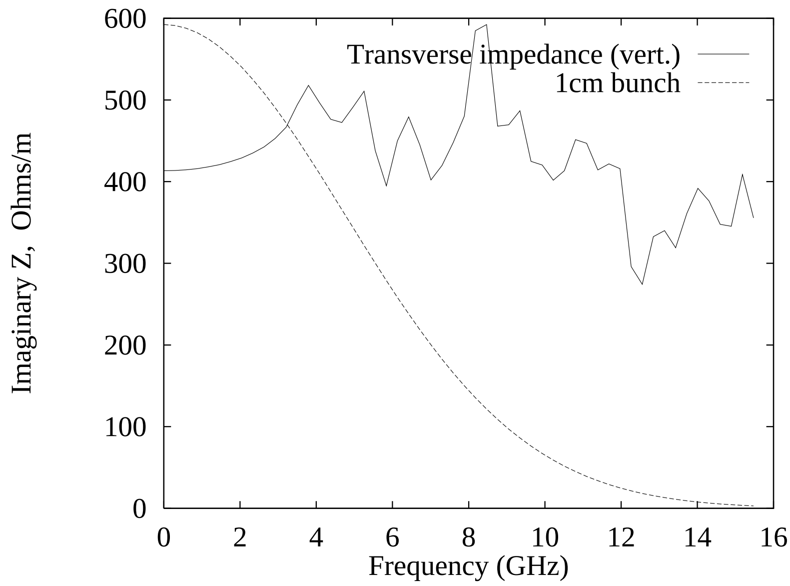


Figure 36: Imaginary part of the transverse impedance (vertical plane).

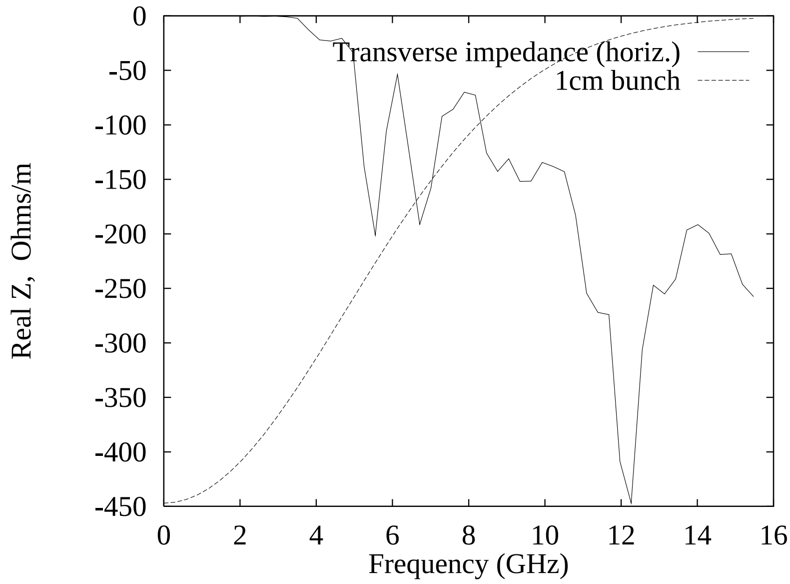


Figure 37: Real part of the transverse impedance (horizontal plane).

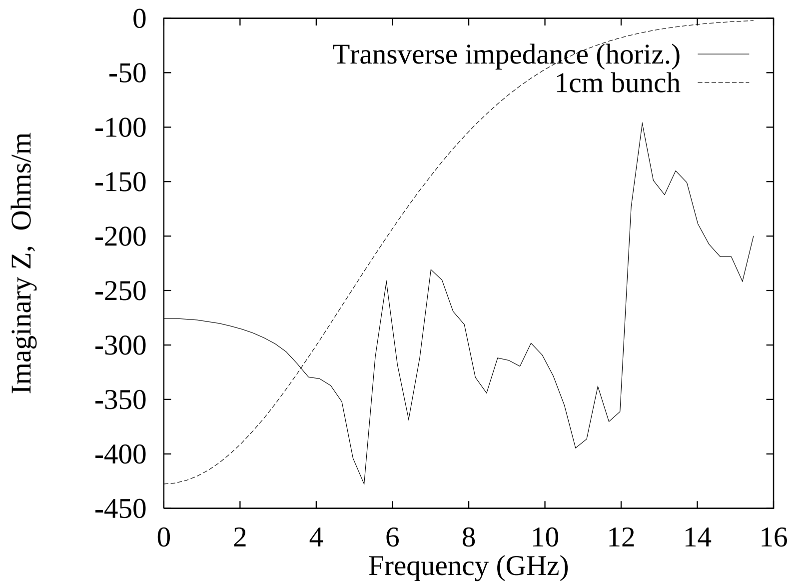


Figure 38: Imaginary part of the transverse impedance (horizontal plane).

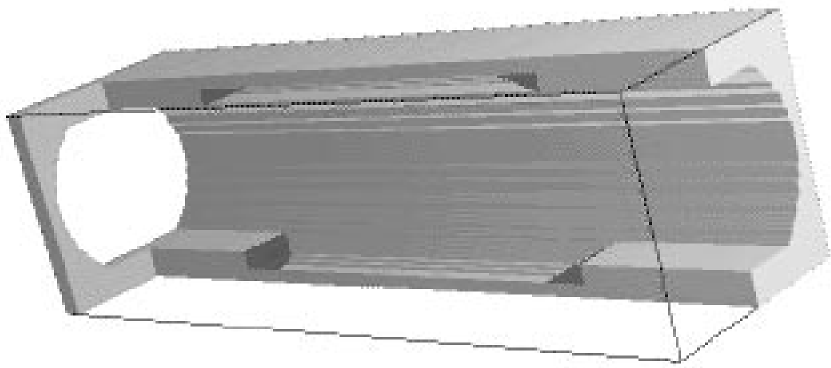

Figure 39: Geometry used in the calculations (transition length $d = 10$ mm).

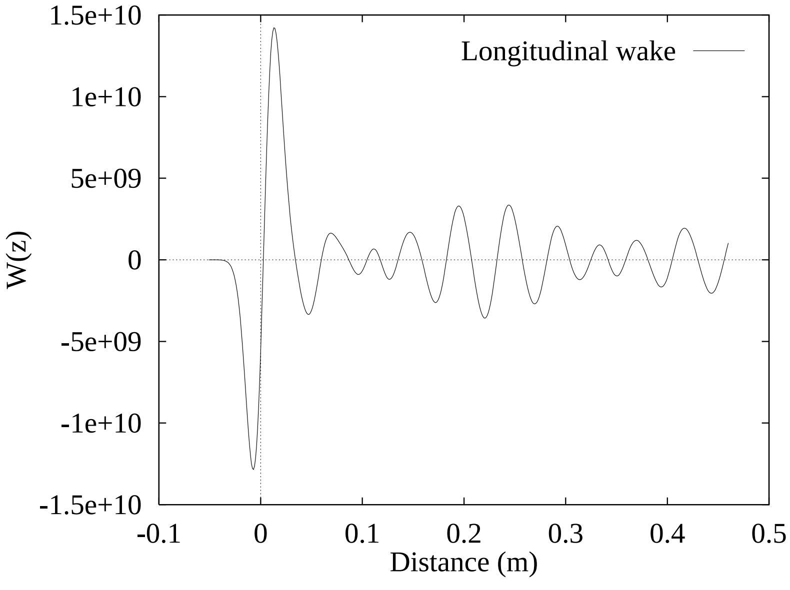


Figure 40: Longitudinal wakefield.

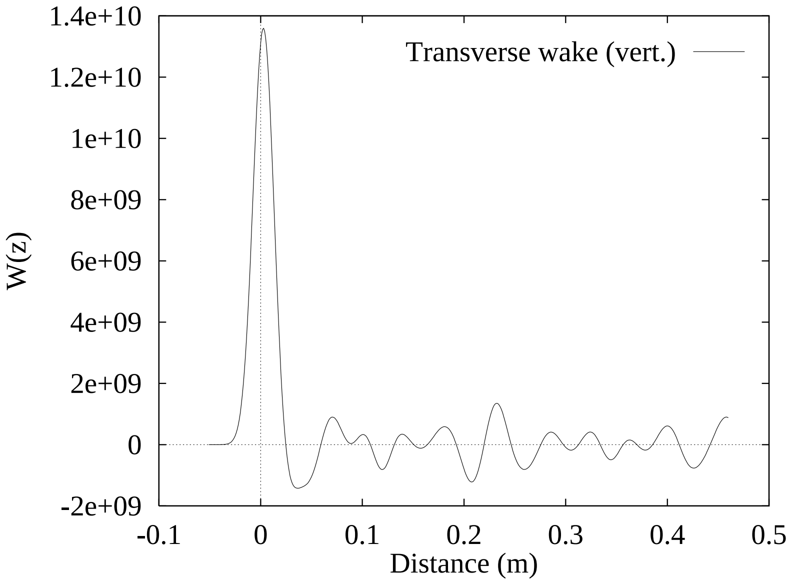


Figure 41: Transverse wakefield (vertical plane).

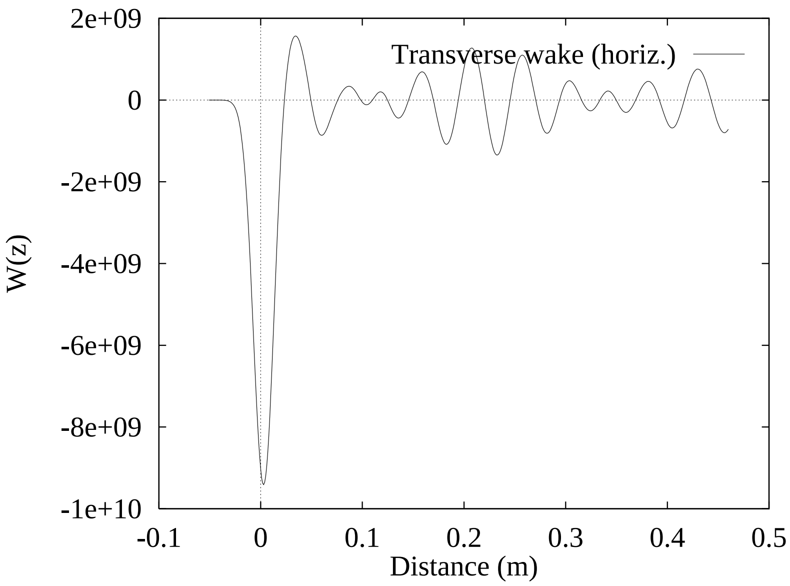


Figure 42: Transverse wakefield (horizontal plane).

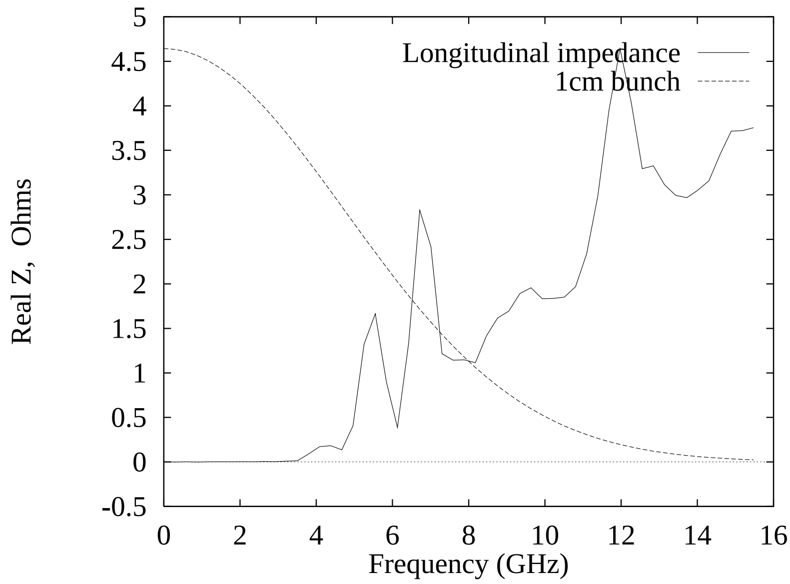


Figure 43: Real part of the longitudinal impedance.

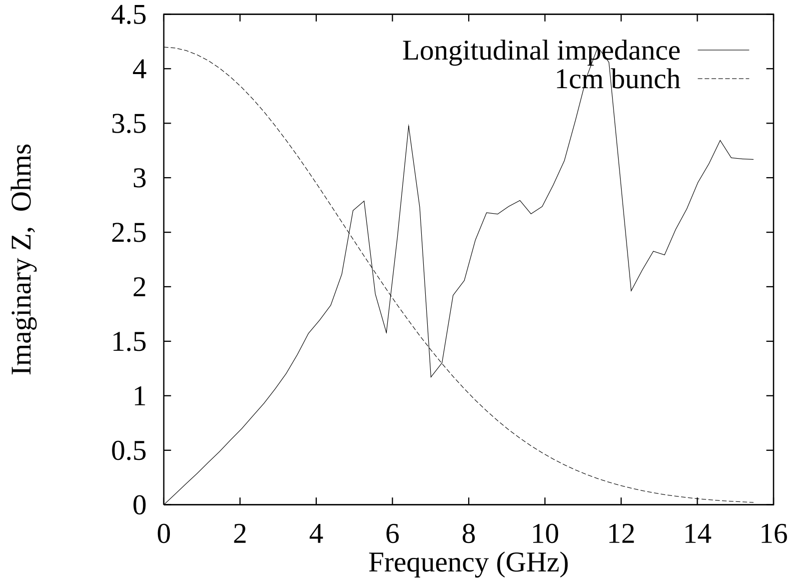


Figure 44: Imaginary part of the longitudinal impedance.

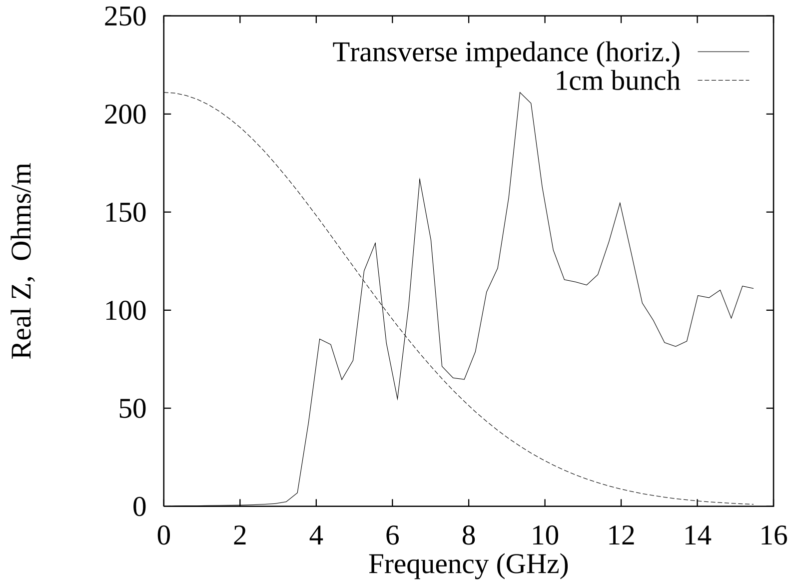


Figure 45: Real part of the transverse impedance (vertical plane).

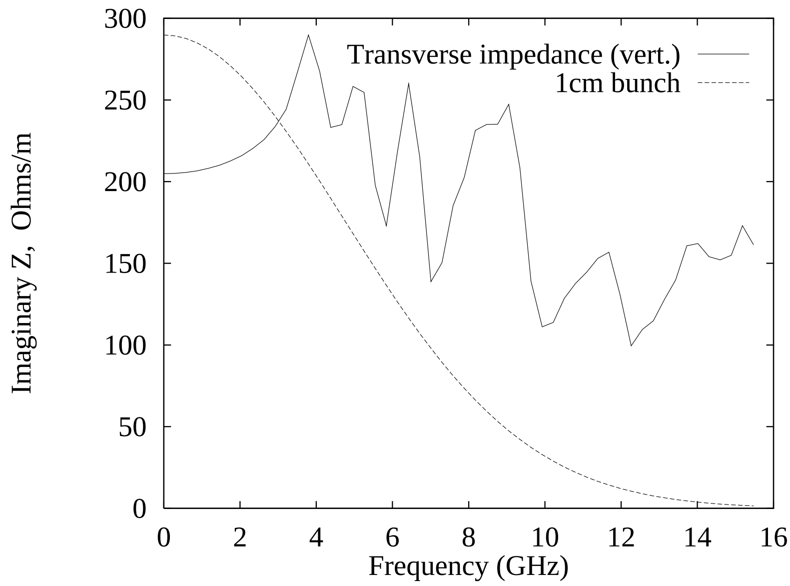


Figure 46: Imaginary part of the transverse impedance (vertical plane).

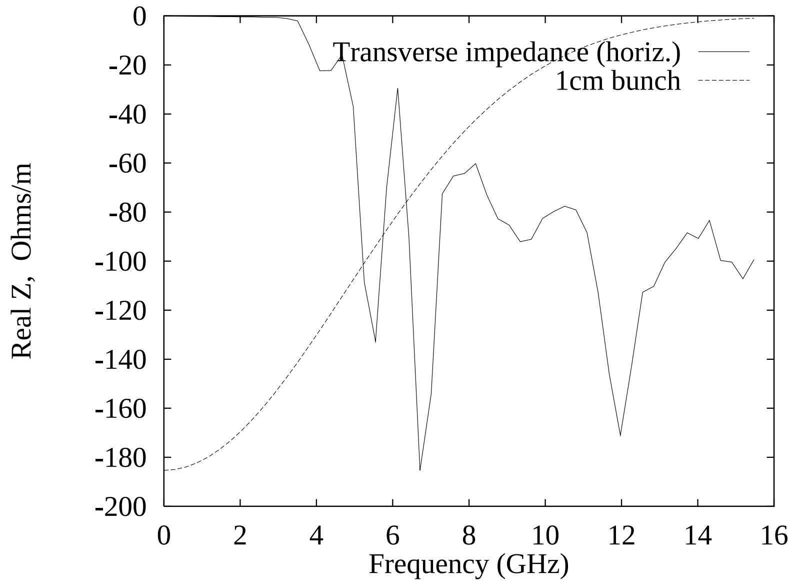


Figure 47: Real part of the transverse impedance (horizontal plane).

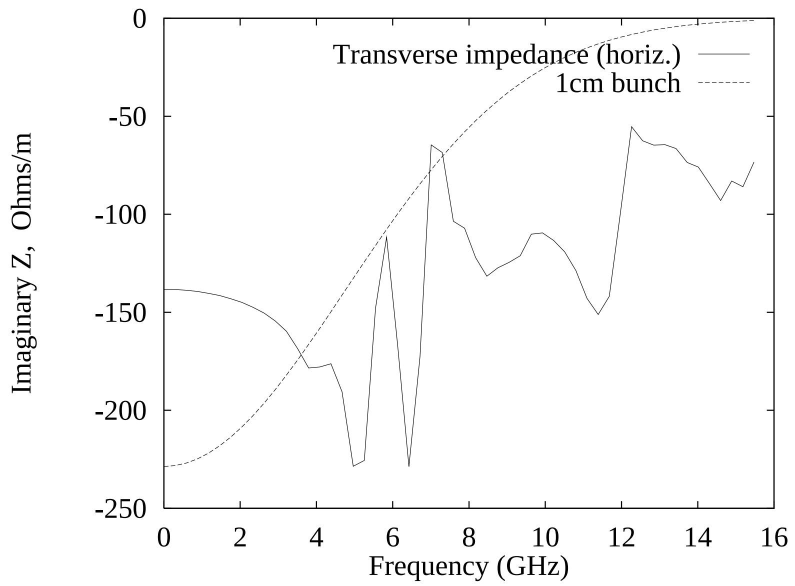


Figure 48: Imaginary part of the transverse impedance (horizontal plane).

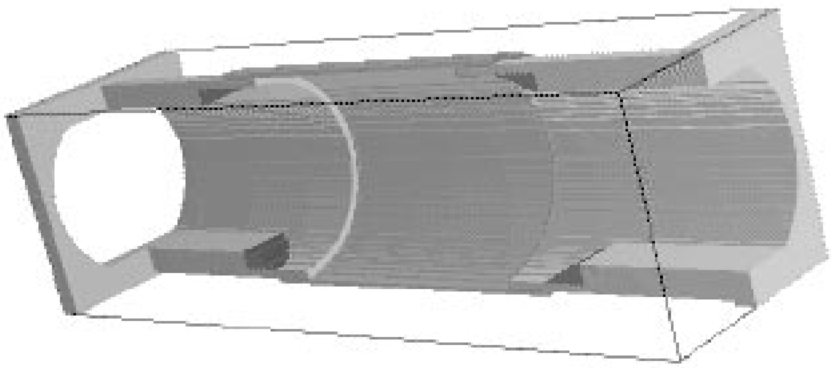

Figure 49: Smooth transition ($d = 10$ mm) and two steps.

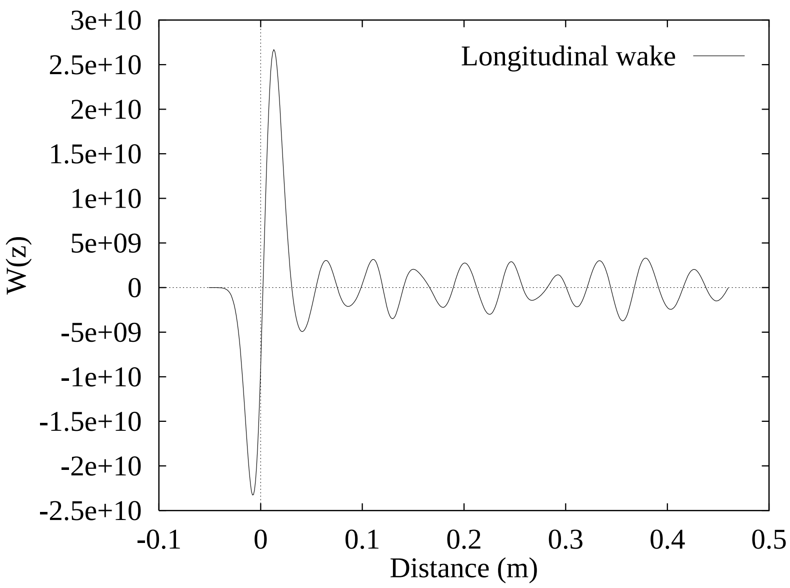


Figure 50: Longitudinal wakefield.

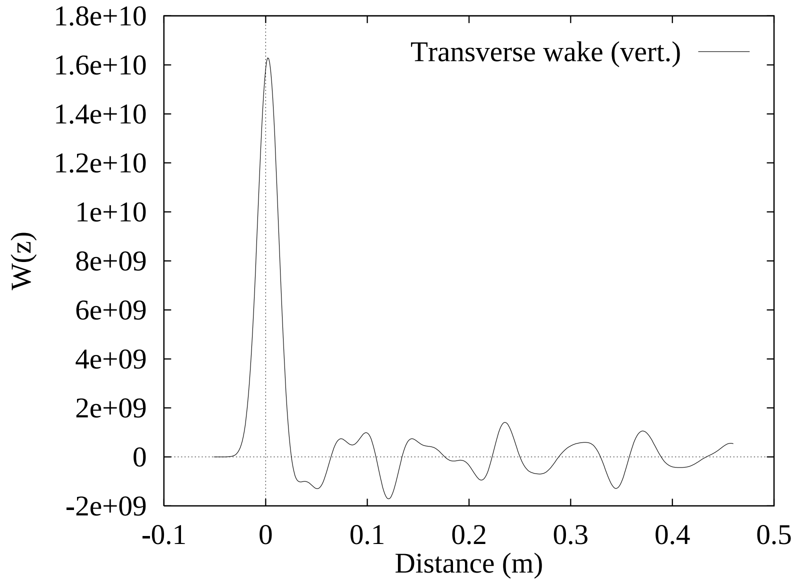


Figure 51: Transverse wakefield (vertical plane).

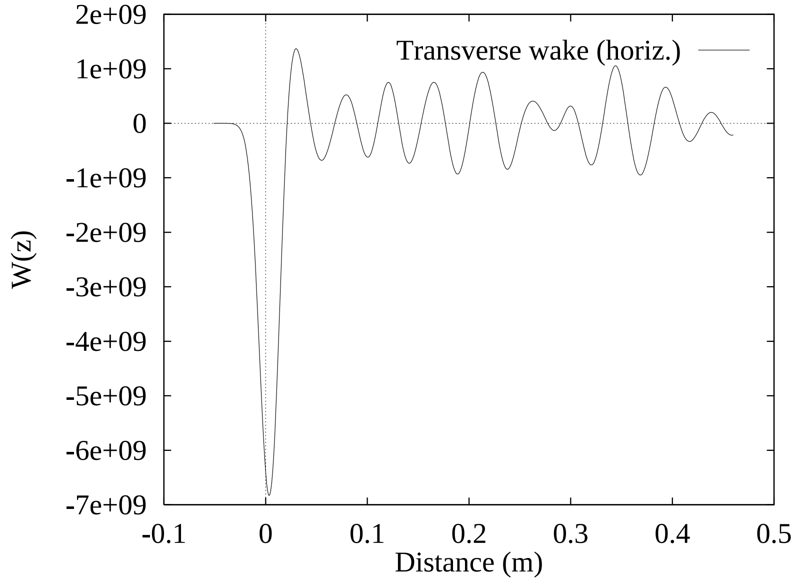


Figure 52: Transverse wakefield (horizontal plane).

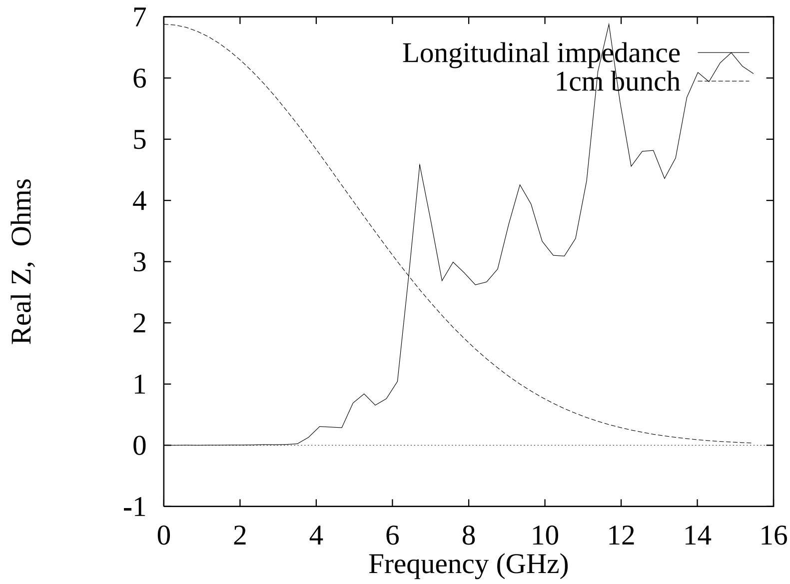


Figure 53: Real part of the longitudinal impedance.

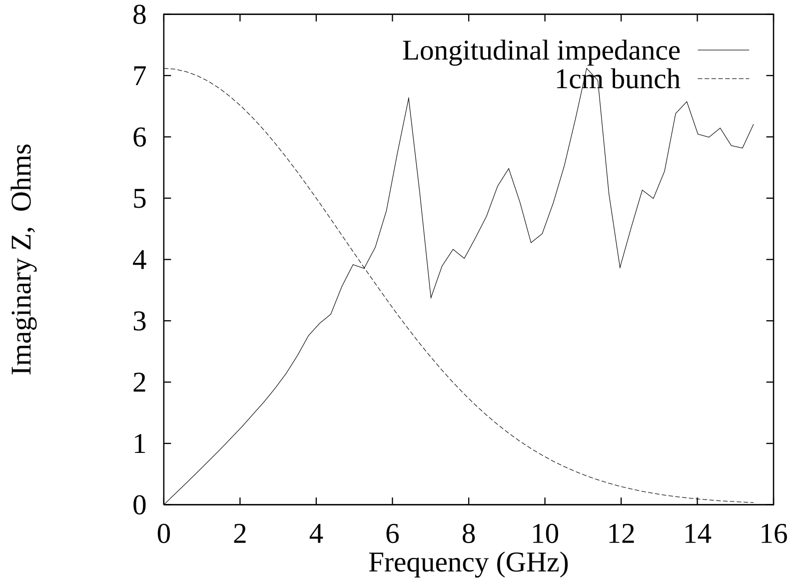


Figure 54: Imaginary part of the longitudinal impedance.

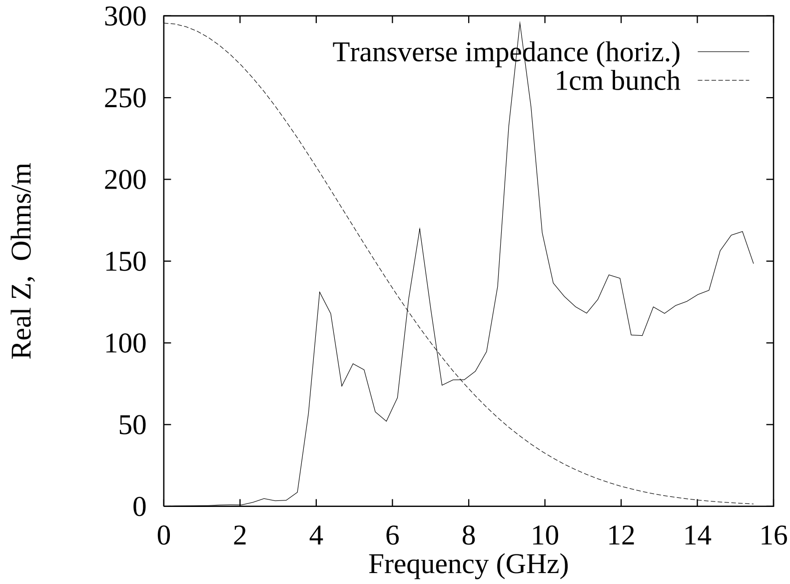


Figure 55: Real part of the transverse impedance (vertical plane).

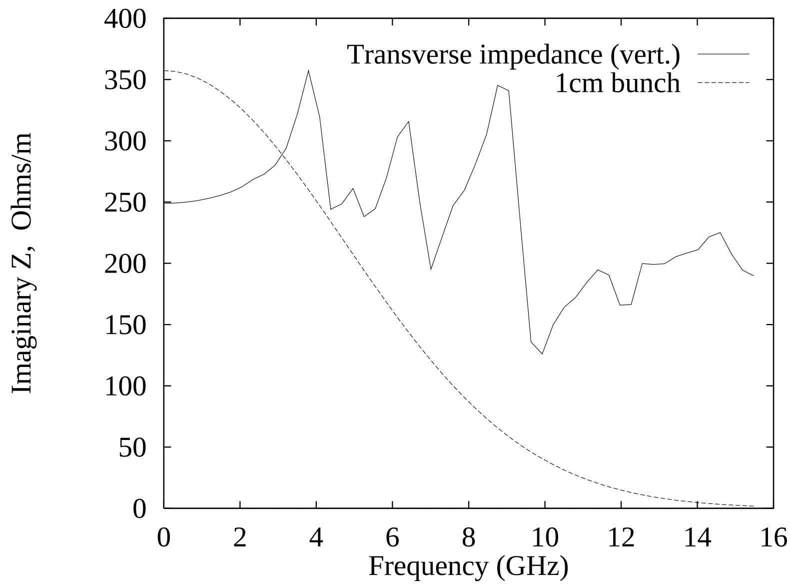


Figure 56: Imaginary part of the transverse impedance (vertical plane).

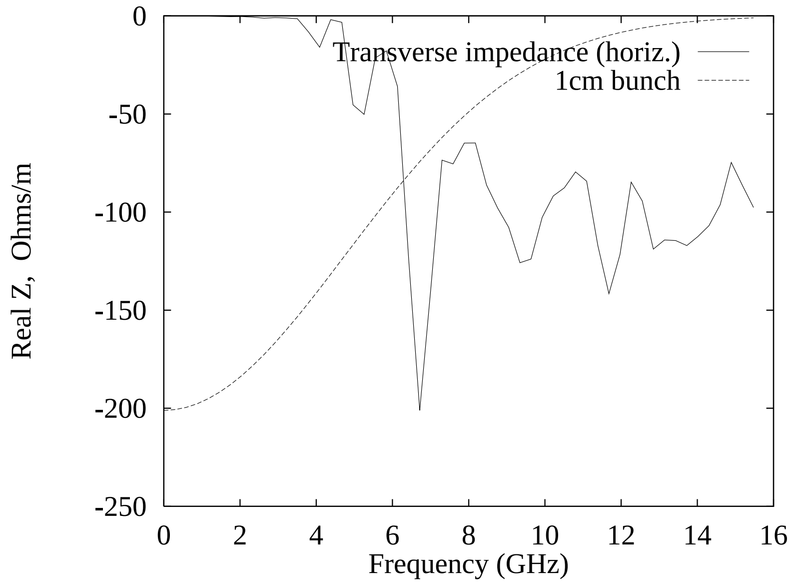


Figure 57: Real part of the transverse impedance (horizontal plane).

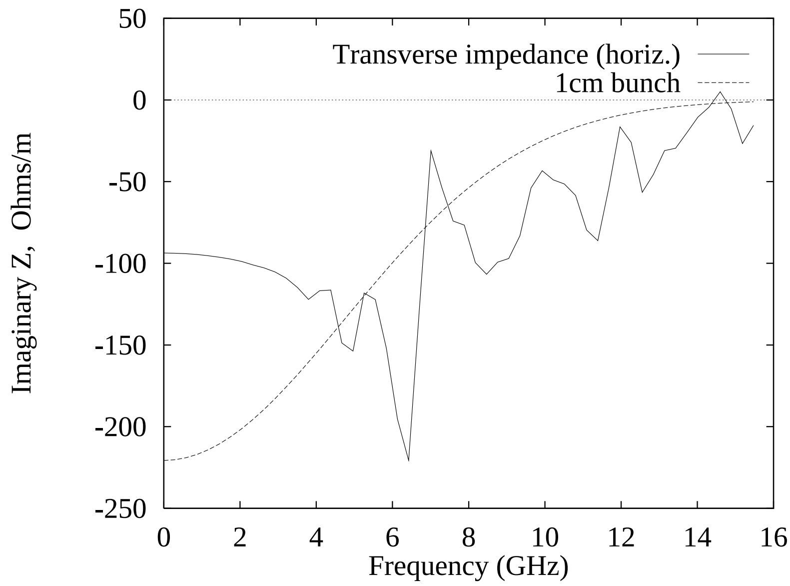


Figure 58: Imaginary part of the transverse impedance (horizontal plane).