CERN Summer Student Project Report

# Faulty Connections in the Beam Position Monitors and their effect on the Beam

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22/08/2019

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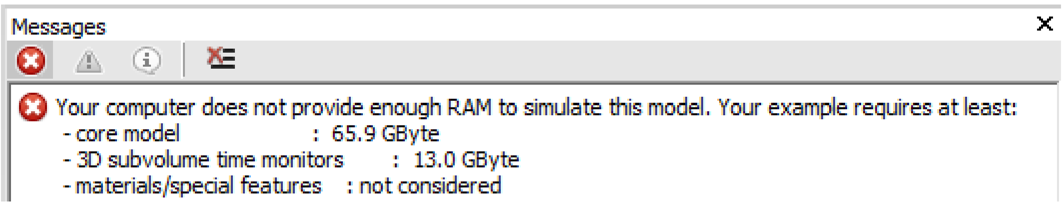
# Acknowledgements

First of all it has been a tremendous pleasure to work at CERN (especially BE-ABP-HSC). It was one of my dreams to pay a visit to the site but I never expected to have the chance to actually work here. Big thanks goes to the summer student team and all the summer students who made this summer unforgettable. Special thanks to my supervisors Benoit and Carlo for teaching and explaining me new things and for helping me with the project. And last but not least thanks to Joel Daricou and Christian Boccard for providing us with the actual BPM and helping us with the measurements.




*Be careful when playing with the mesh cell and monitor parameters!*

# 1. Introduction

In the BE-Newsletter issue 24 in December 2018 it was introduced that the instabilities regarding the PSB extraction kicker were produced by unmatched termination of cables. The same type of vertical instabilities were also seen in LEIR. This was also caused by a mismatch at the strip-line beam position monitors (BPM) [1] [2]. A BPM is a device used to measure the position of the beam by measuring the voltage produced by the beam. Comparing the voltage to a BPM on the opposite side, the vertical and horizontal coordinates can be calculated assuming the beam has a Gaussian distribution.

The purpose of this project was to study how different terminations e.g. unmatched impedances, shorted or open cables in the BPMs affect the beam and cause instabilities. For this project we were given a test bench version of a BPM as seen in figure 1 which was used for initial measurements. Based on the technical drawings of the device a CST model was also constructed for the purpose of further study. The measurements and the simulation results were then compared to prove that the CST model was accurate enough to be used for further studying of the effects. Many different simulations were performed to obtain the results introduced at the end of this report.

Workflow of the report:

- Constructing the model(s)
- Measurements on the device
- Comparison between the simulation results and measurements
- Further study (wakefields, wire model, terminations) and comparison

Due to some problems and practical reasons the modelling and the measurements took place at the same time during the project.

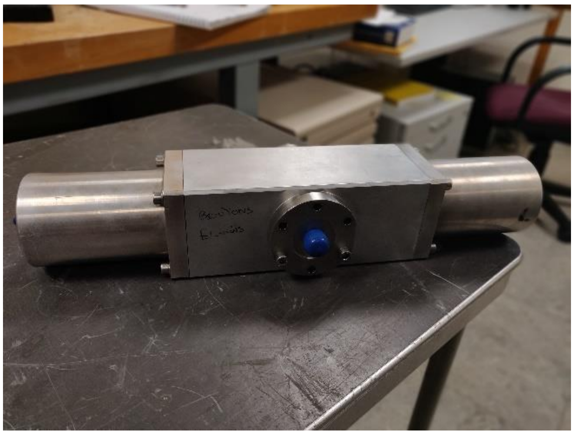


Figure 1: (Left) Test bench device used for measurements including two button BPMs on the opposite sides, “beam” propagation from left to right. (Right) A button BPM.

# 2. The CST models used for simulations

The construction of a 3D model was the first step in the project. At first a very simple model (included in the appendix) with very simple geometry was produced to see if it would match the measurements at all. It provided good approximate results and a refined version with all the previously missing details added, was modelled. The final model and cross-section of it are introduced in figure 2 & 3.

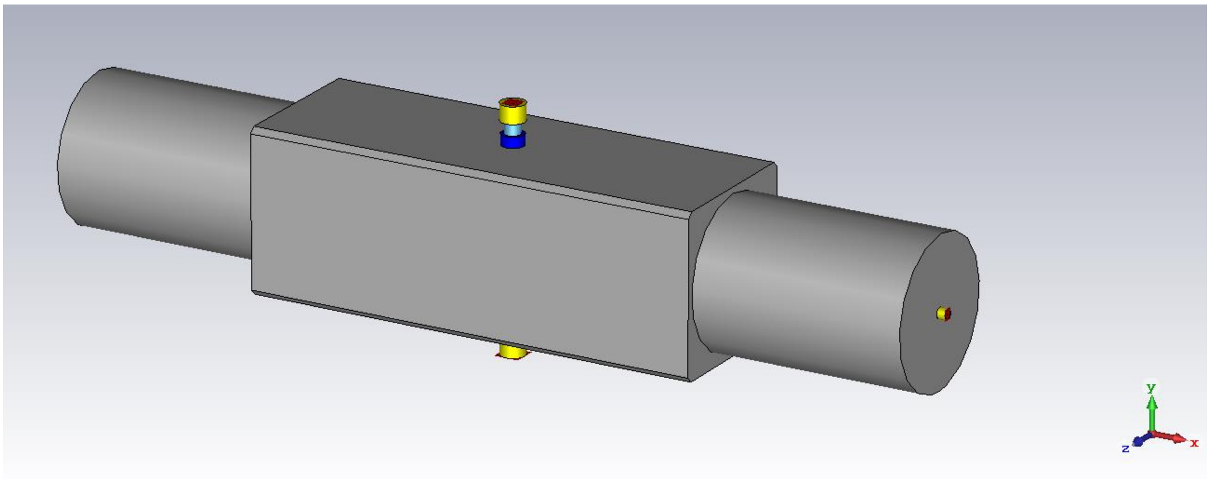


Figure 2: The final model

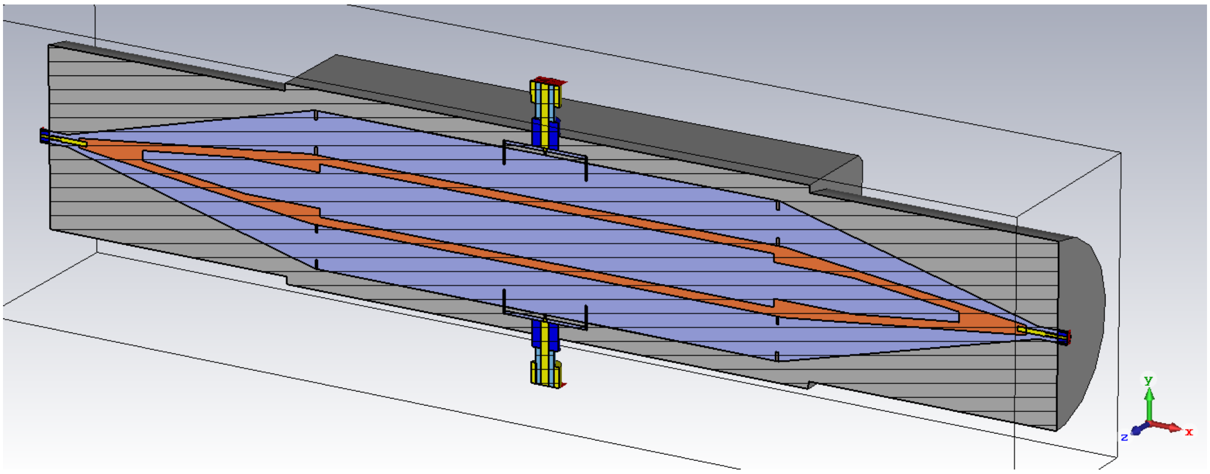


Figure 3: Cross-section of the model.

In addition another model was also made in order to simulate the beam in the CST Wakefield solver and based on the Wakefield model the fourth model called the Wire model was produced. These models are introduced in figure 4 & 5.

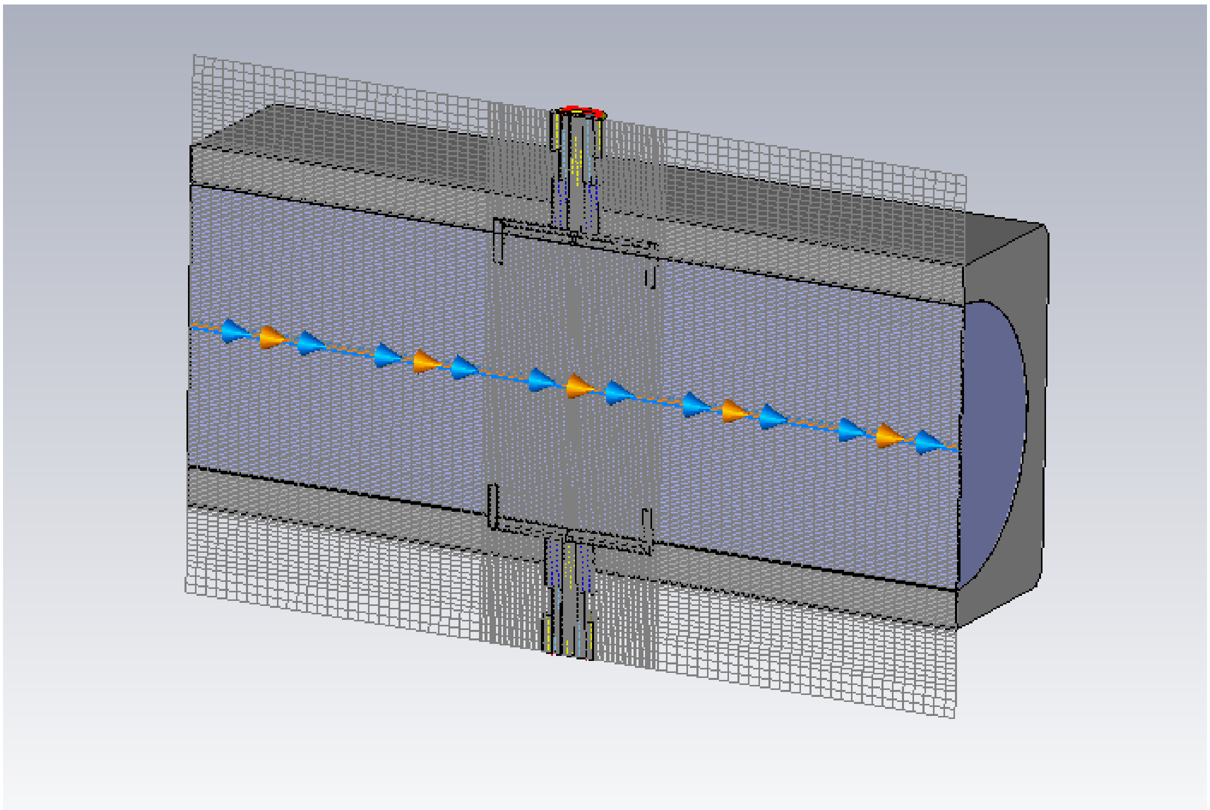


Figure 4: The model used in Wakefield solver, beam propagation along the x-axis.

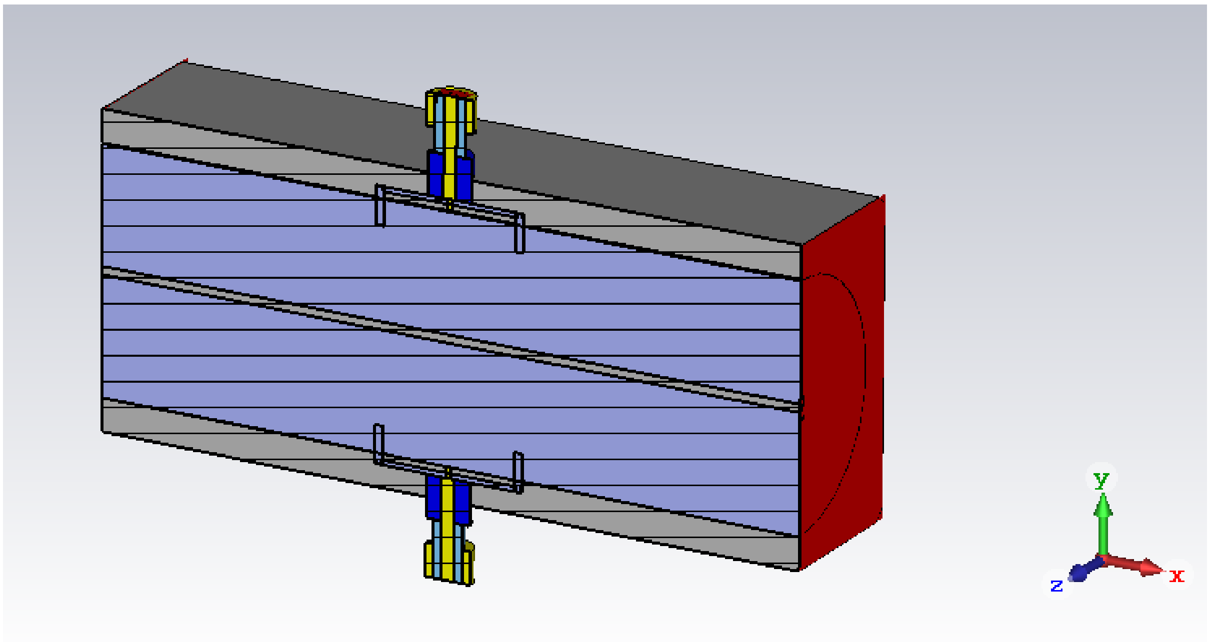



Figure 5: The Wire model.

These models are referred in the upcoming sections of this report and were used to produce the results explained later.

# 3. Measurements

The initial measurement setup consisted of a VNA (Vector Network Analyzer), 4 cables each connected to the device and with the BPMs itself. The initial setup is introduced in figure 6. The main focus of these measurements was to capture the different scattering parameters (S-parameters) in the frequency range of 100 Hz to 3 GHz. The $S_{11}$ is associated to the reflection coefficient parameter and the $S_{21}$ to the insertion loss or "the power received by port 2 from port 1". The S-parameters are widely used in cavity measurements to characterize resonance parameters (resonant frequency, quality factor and shunt impedance). In the case of the project they were used to detect modes and differences between each termination.

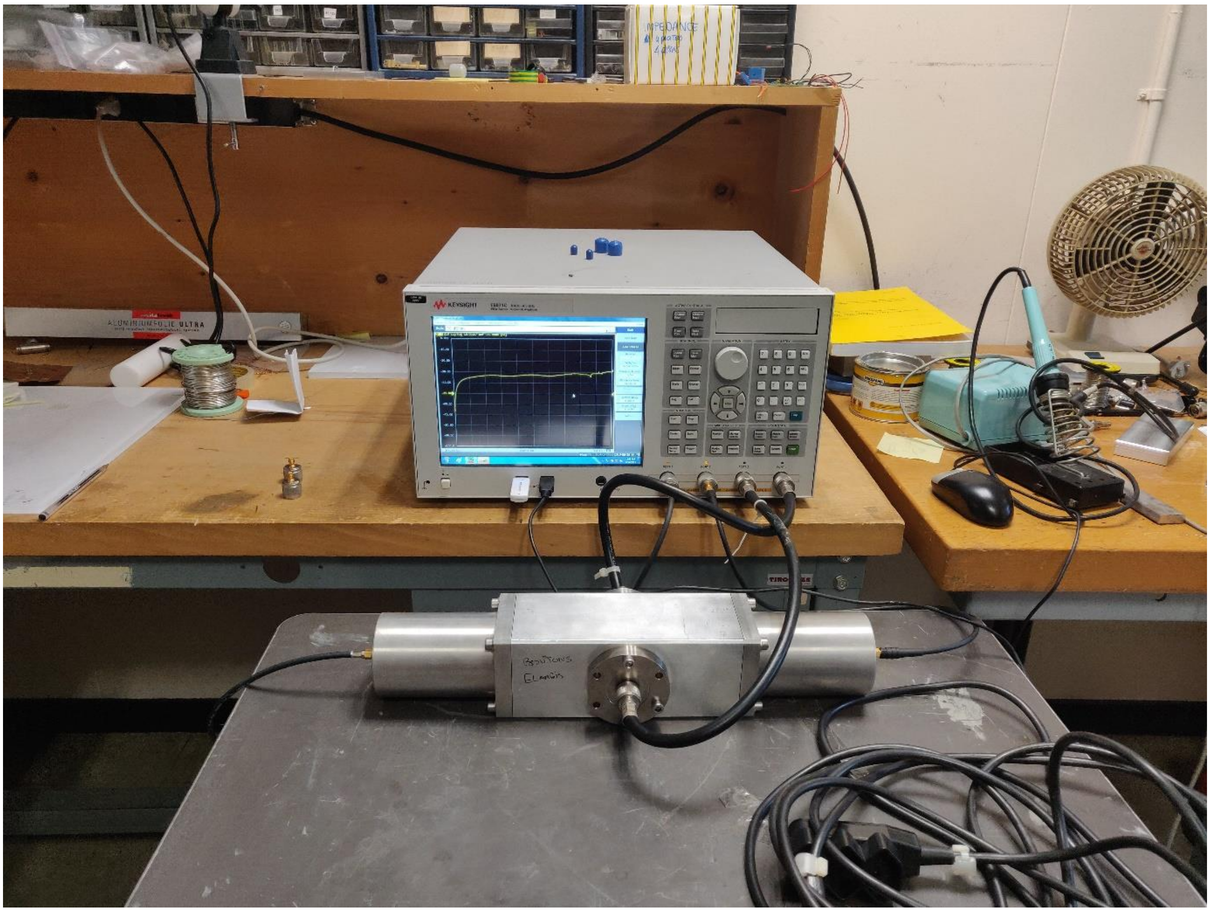


Figure 6: Initial measurement setup with all the cables connected

The initial setup was used at first but there were some problems involved with the calibration of the cables. The cables had adapters attached to them because they were needed to connect the SMA cables to the electronic calibration kit and with them removed to connect the cables to the SMA input of the port of the DUT. This caused some minor errors in the calibration. To solve the problem the measurements were done using an SMA calibration kit. Therefore, no adapters were required in both calibration and measurements. Below in figure 7 & 8 are shown the comparisons of the $S_{11}$ and the $S_{21}$ parameters between the original setup and the SMA measurements.

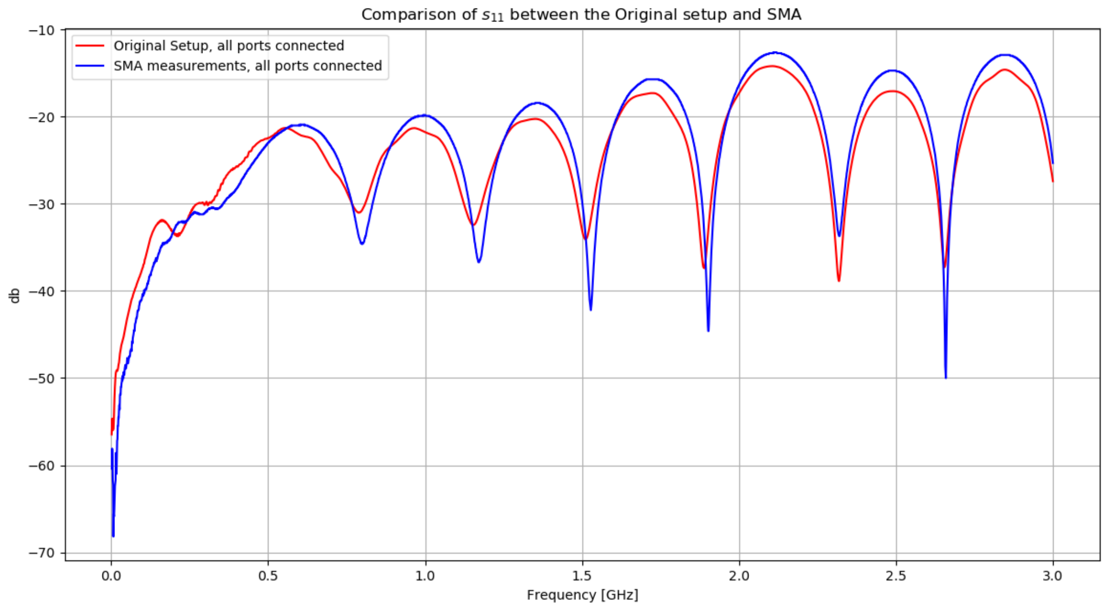



Figure 7: Comparison of $S_{11}$ between the original and SMA

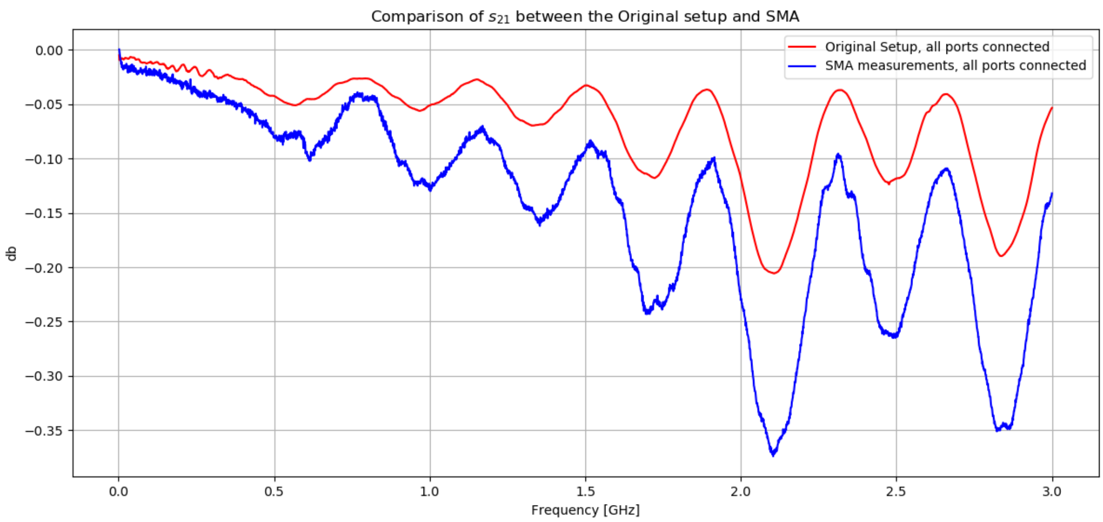



Figure 8: Comparison of $S_{21}$ between the original and SMA

# 4. Different Simulations and Results

In this section we discuss about the different simulations and their results.

## 4.1 Results

The very first simulations were done in the CST frequency domain solver in order to get the wanted scattering parameters $S_{11}$ and $S_{21}$. The simulations were done first with all ports matched and then one port shorted. The model used is the same as in figs 2 and3. Comparisons between the measurements and simulations are presented in figs 9 and 10.

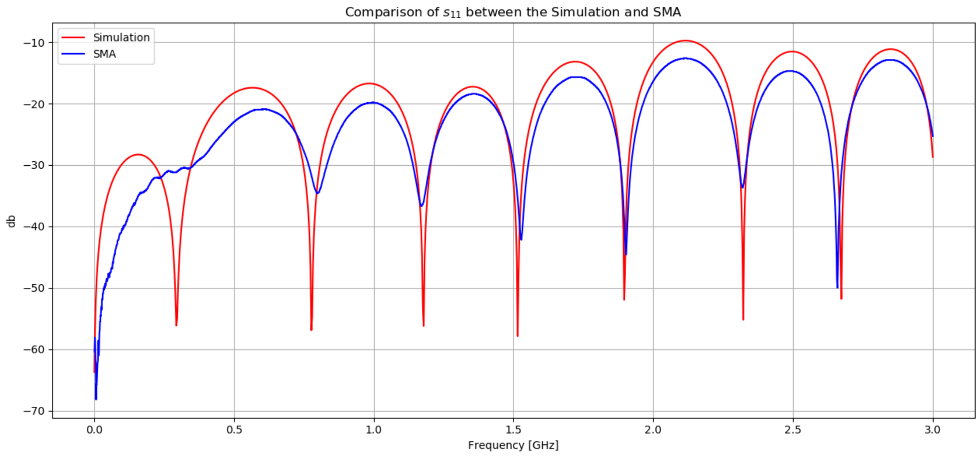



Figure 9: $S_{11}$, Comparison between the measurement (SMA) and the CST simulation.

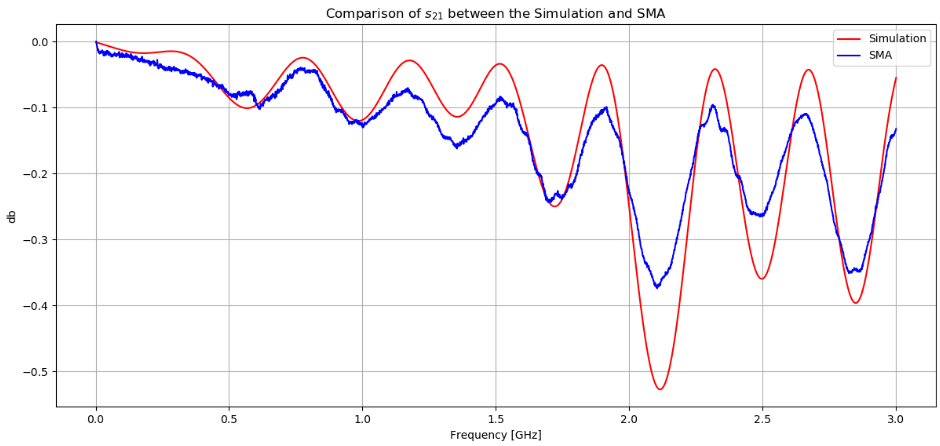



Figure 10: $S_{21}$, Comparison between the measurement (SMA) and the CST simulation.

The next simulation and measurement were done by shorting one of the ports. In the measurements a coaxial short was connected directly to the BPM button and in the simulation the short was modeled with the schematic tool of CST which allows connecting circuit elements to the ports. In the figure 11 for $S_{21}$ the results are shown.

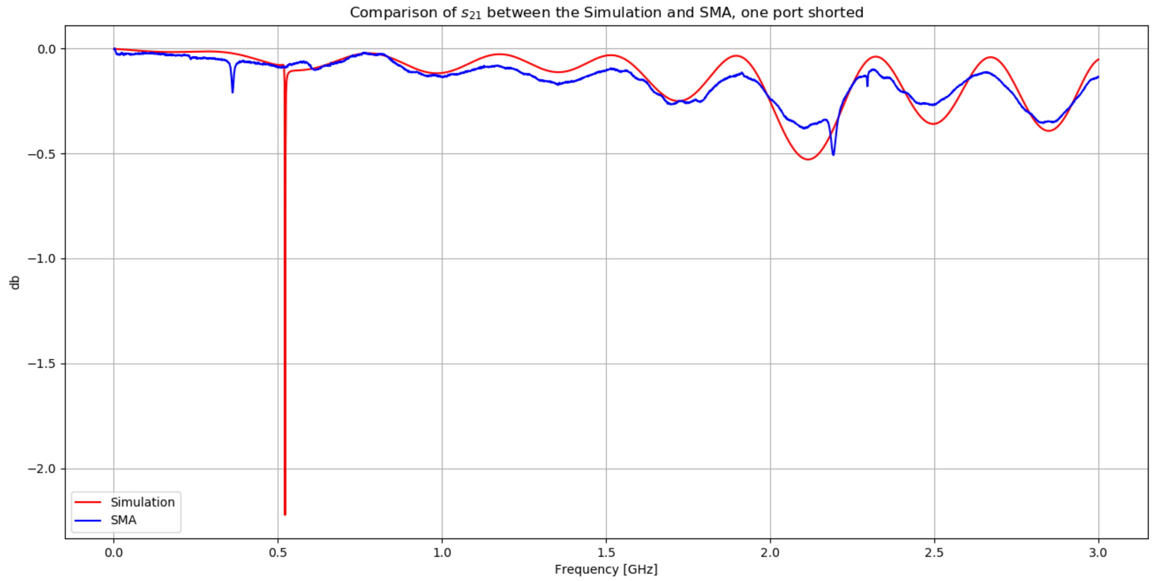



Figure 11: The $S_{21}$ of measurements and CST Simulation, one BPM button shorted

Because of the spike in the measurements it was decided to narrow the frequency range to 0 – 1 GHz. The spike in the simulation is questionable and will be discussed in the analysis. At this point the conclusion was that the model is accurate enough to be used to do further simulations.

The model pictured in the figure 4 was used next in the Wakefield solver to see the effect of a simulated beam. The matched and one port short cases were simulated and the key focus was on the wake potential and wake impedance. The beam is located directly in the centre of the model and the beam propagation is along the x-axis which makes the x-component the longitudinal impedance / wake potential, y-component is the transverse vertical and z-component is the transverse horizontal. In figure 12 & 13 the comparison of wake impedance between the matched and shorted case is shown. Red curve is the shorted case and blue is the matched one. The z-component in left out because there was no major differences in it. In the figure 14 and 15 the wake potentials between matched and shorted case are introduced.

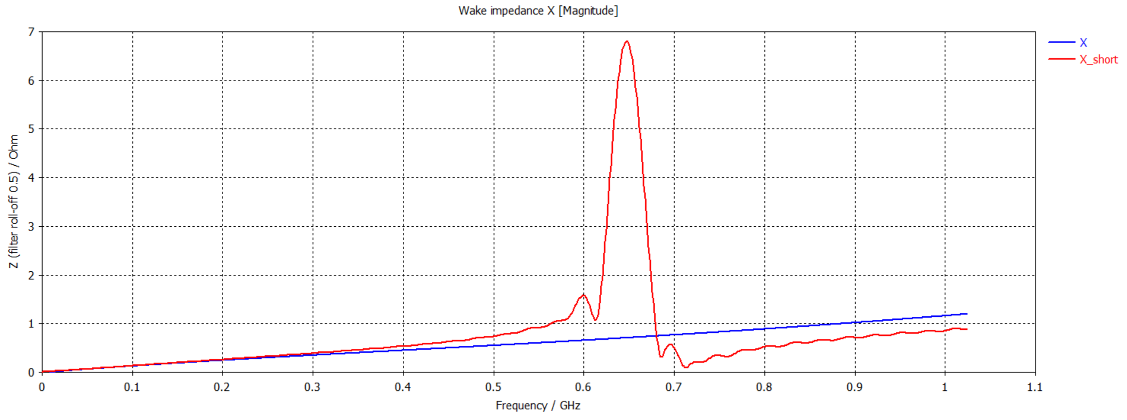



Figure 12: Longitudinal Wake Impedance between the matched and shorted case

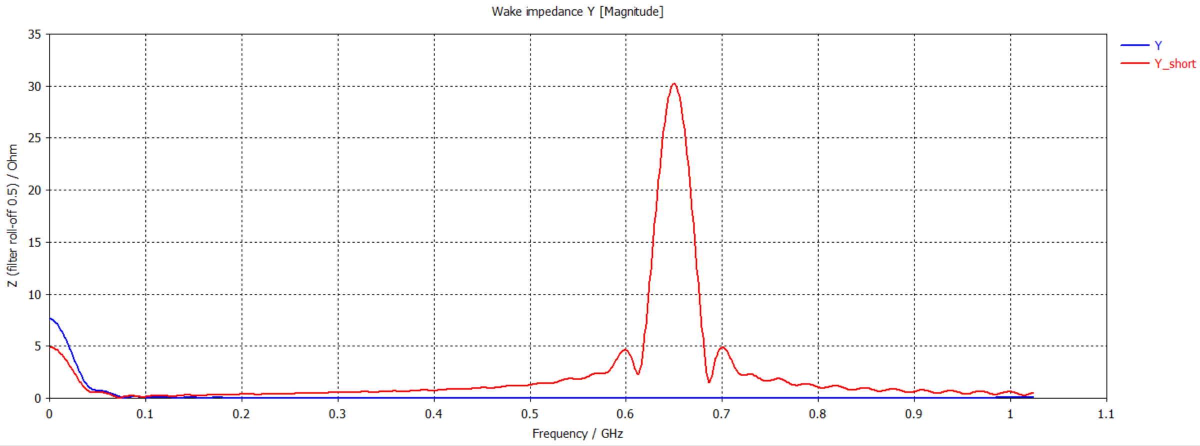



Figure 13: Transverse vertical Wake Impedance between the matched and shorted case

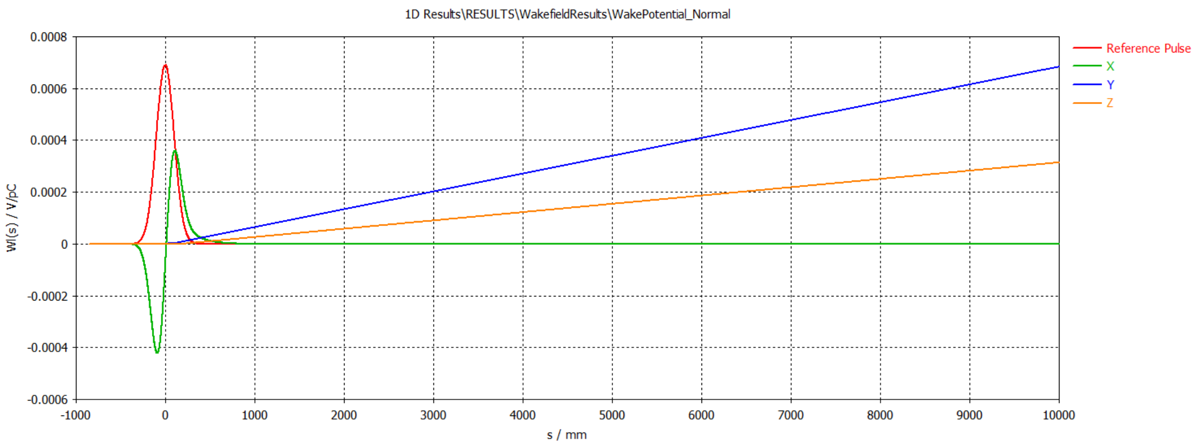



Figure 14: Wake potentials of the matched case

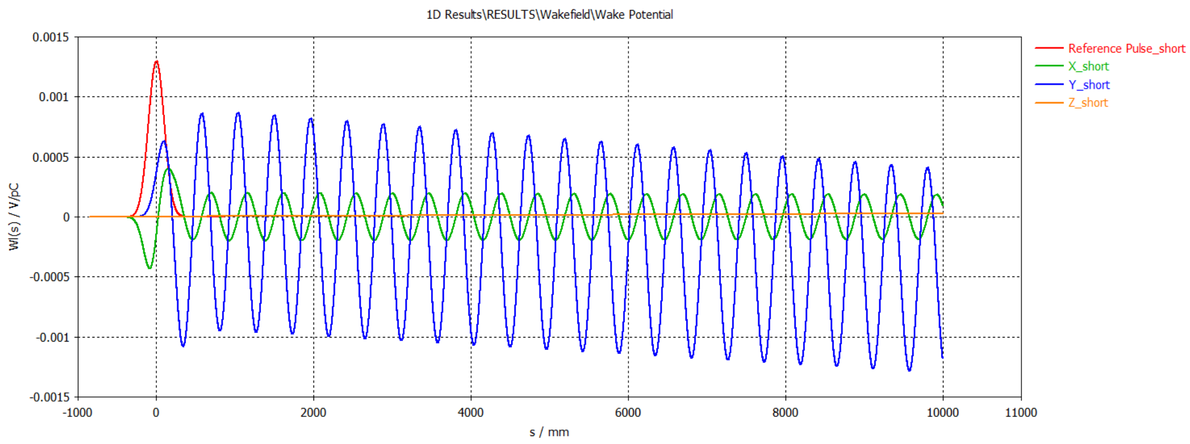



Figure 15: Wake potential of the shorted case

## 4.2 Analysis

In this part the figures and results from the previous section are further analyzed and explained.

### 4.2.1 First measurements and simulations

From the figure 9 & 10 we can see that the simulations of the model and the results from the measurements match pretty well. The different modes are found on the exact same locations from 0.7 GHz onwards. The only minor difference is the amplitude but regarding the simulations it should not matter. The major difference is the period before 0.7 GHz where the curves do not match that well. This is further seen in the figure 11. At this point it is not known for sure why this problem exists. There have been speculations that it would have something to do with the connections but at this moment there is no proof.

The other interesting thing if we look at the figure 11 is that the simulations provide a very sharp spike at the 0.52 GHz frequency. The problem is that it is generated randomly e.g. sometimes the simulations do not produce the spike and sometimes they do. Because of the nature of the spike and the inconsistency it was suggested that it is a problem in CST and could be disregarded. More or less the spike was produced when the short was modeled with the schematic tool of CST. The spike is not observed when the short is directly modeled in the 3D structures with perfect electrical conductor (PEC).

### 4.2.2 Wakefield Solver

The Wakefield solver produced some interesting results concerning the effect on the beam coupling impedance. Seen from the fig. 12 and 13 the shorting of one of the ports produces a different curve than the matched case and to be more precise a huge spike is formed at 0.65 GHz in the longitudinal and transverse vertical components. When we compare the wake potential we can also see that the plots are way different. In the shorted case the x- and y-components begin to oscillate when in matched case it is not happening. From these results we can already assume that different cases other than the matched affect the beam in some way.

# 5. The Wire Model

In order to study these effects further a new model was produced. Schematic tool is very useful in simulating different termination with different length of cables but we cannot use it in the Wakefield solver so we need to go back to frequency domain. In this model the beam introduced in the Wakefield solver is replaced by a thin wire which simulates it. The model used is introduced in fig. 5 where you can see the wire instead of a beam. There are two ports located at the ends of the BPMs which will be used in the schematic to model different terminations. In fig. 16 the initial setup schematic of the model is introduced. The two ports are connected to a coaxial cable which length varies the initial one being *L = 0 mm*. The simulations were done using the parameter sweep to see what kind of effects the cable length and attenuation in addition to different terminations have.

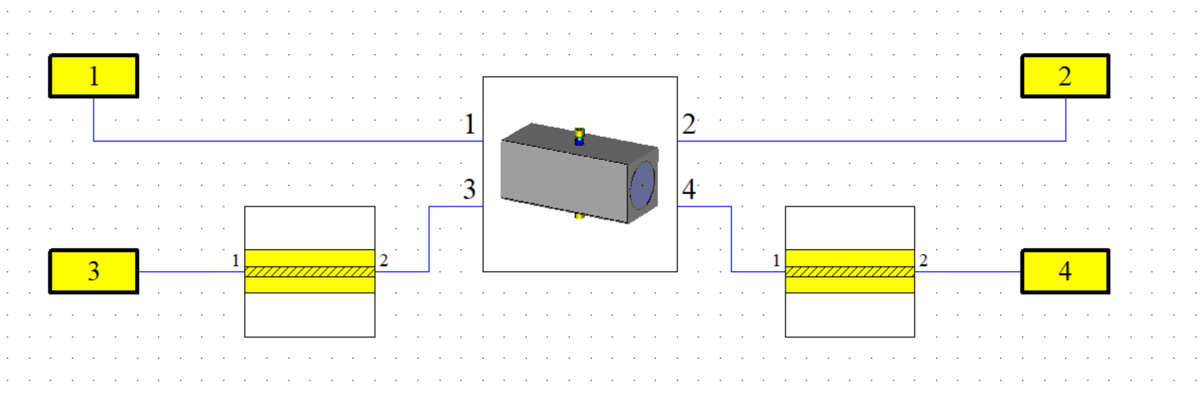



Figure 16: The initial setup in the schematic tool, port 3 and 4 are the BPMs.

The first simulation was to see if the cable length has any effect in the matched case. In figure 17 the results of $S_{11}$ are shown. As expected the cable length (from 0mm to 2000mm) has no effect on the results when the ports are matched. SCL is the parameter used for cable length.

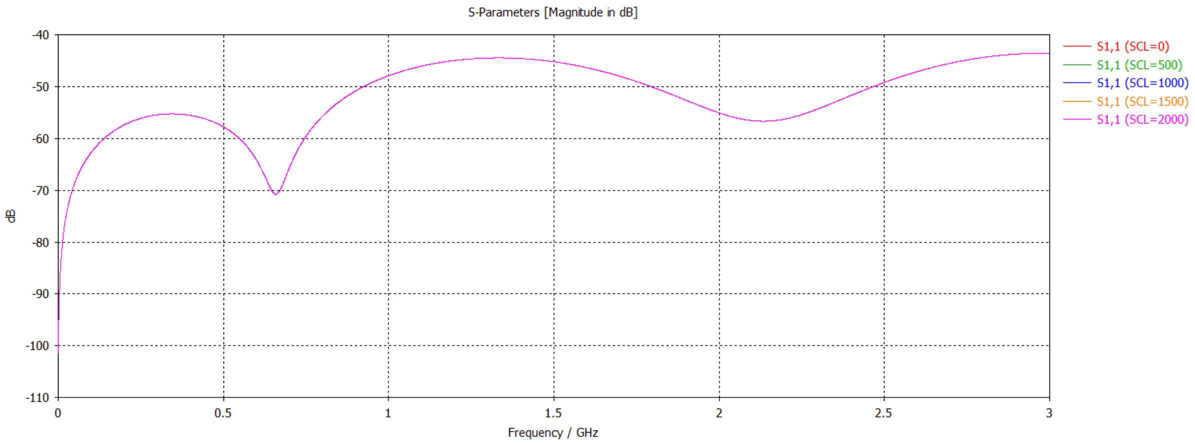



Figure 17: $S_{11}$ parameter of the Wire Model with different cable lengths

In the next simulations different types of termination setups were used to see any effects on the parameters. The setups are listed in the table 1. The first case was already introduced previously.

Table 1: Different simulation setups in the schematic tool.

| **Case number** | **Port 3** | **Port 4** |
|---|---|---|
| **1** | Matched | Matched |
| **2** | Short | Matched |
| **3** | Short | Open |
| **4** | Short | Short |
| **5** | Open | Matched |
| **6** | Open | Open |

## 5.1. Simulations without attenuation

Every setup was also simulated with cable lengths of 0, 500, 1000, 1500 and 2000 mm. The results for the $S_{21}$ in the second case are introduced in the figure 18, 19 and 20.

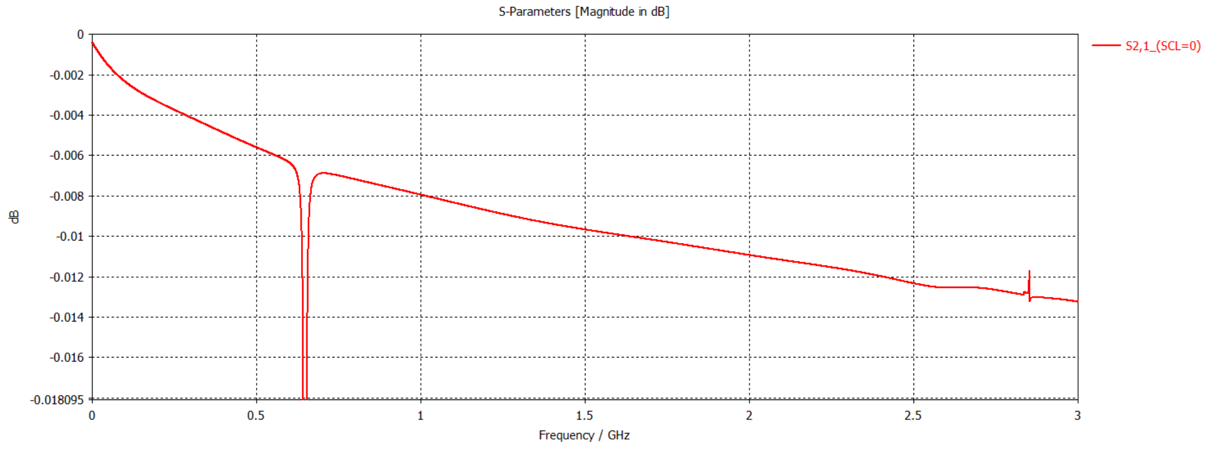



Figure 18: Case 2 $S_{21}$ results with a cable length of 0mm

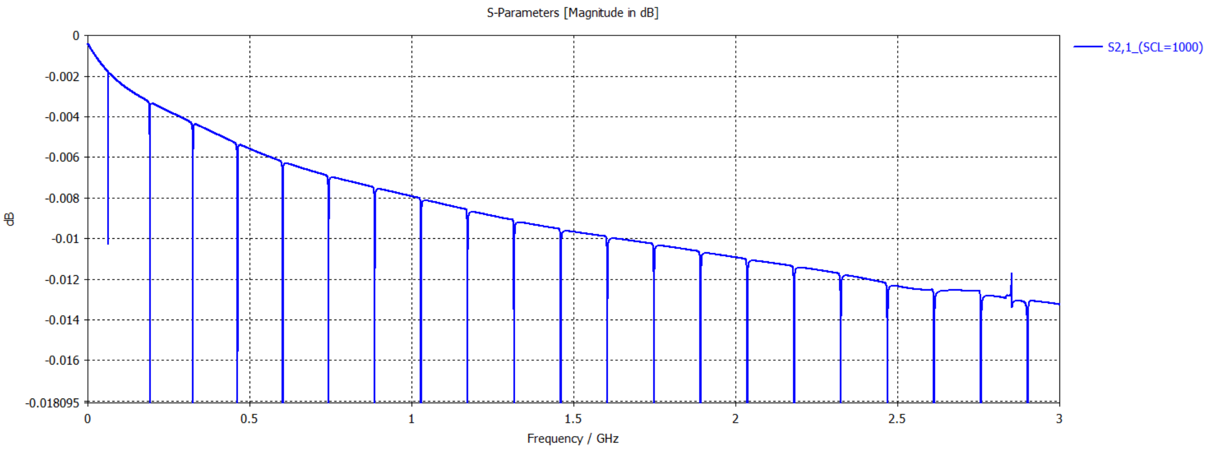



Figure 19: Case 2 $S_{21}$ results with a cable length of 1000mm

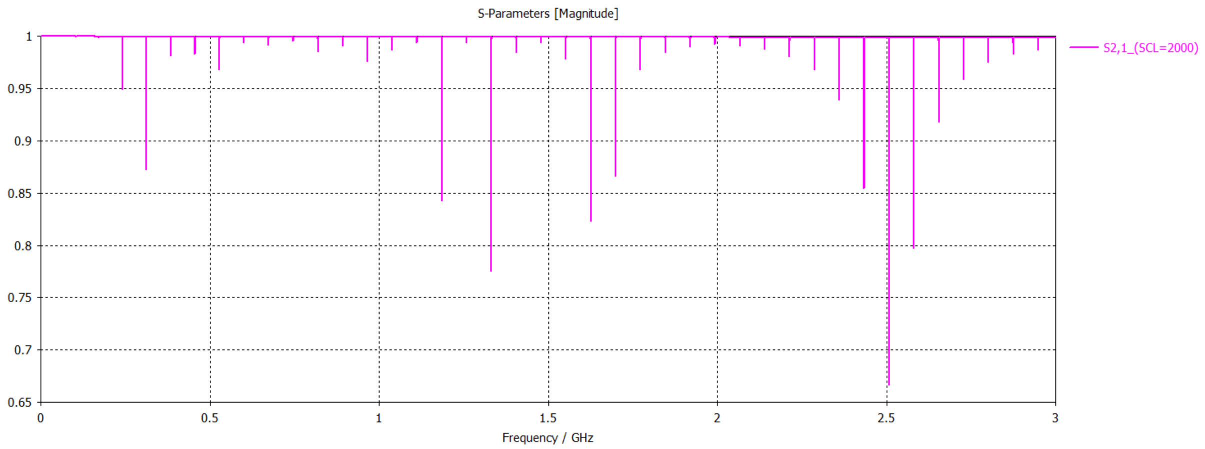



Figure 20: Case 2 $S_{21}$ results with cable length of 2000mm

From the plots above we can see that increasing the cable length with a short termination causes more “disturbances” in the frequency domain. The phenomena happens in every case except the one where both ports are matched so for this reason only the results with cable length of 0 mm will be presented here through figures 21-24. By increasing the cable length the results between the different cases become more or less the same but shifted as shown in the figure 25. As expected the differences between the resonances in case of one kind of a termination is about $\frac{\lambda}{2}$ and the difference between a shorted case compared to an open case is $\frac{\lambda}{4}$ (this is shown later in the figure 28).

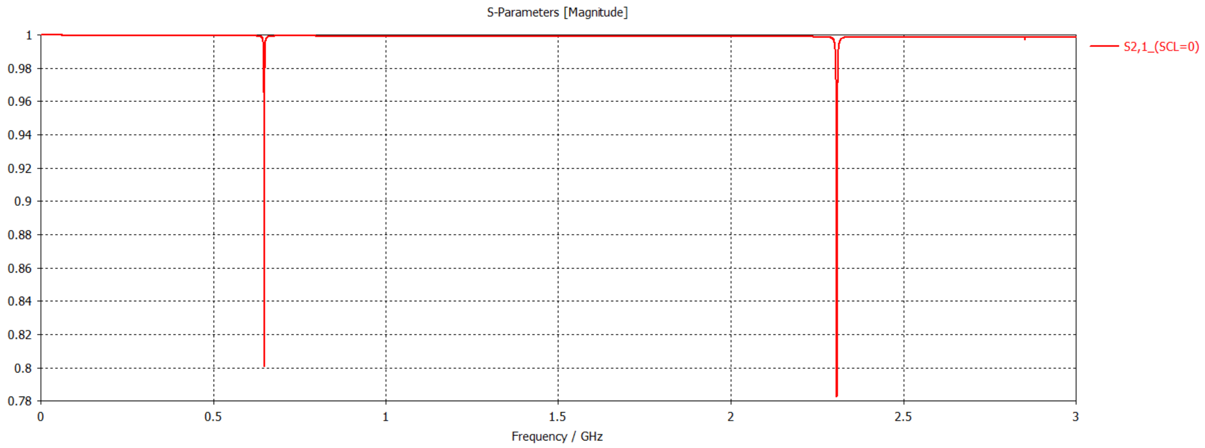



Figure 21: Case 3, S21, port 3 short, port 4 open

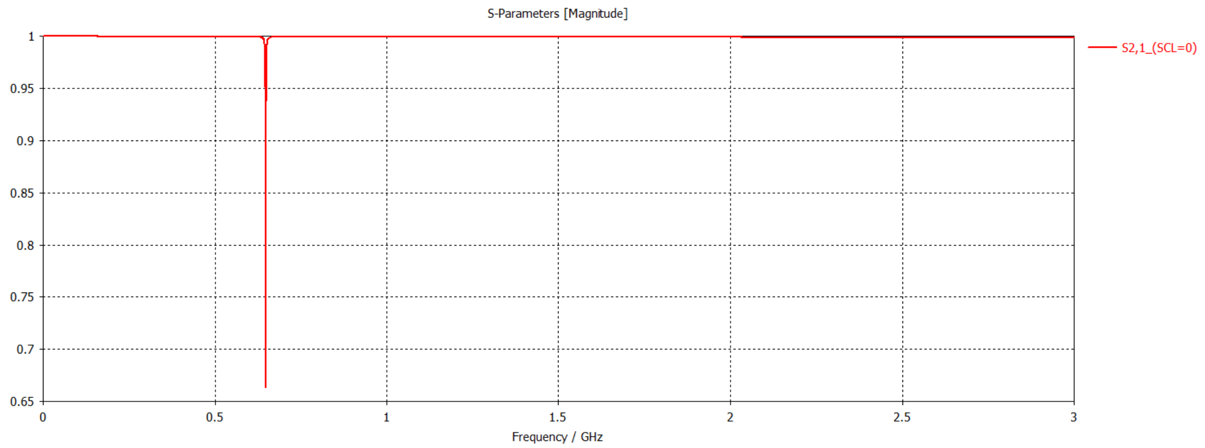



Figure 22: Case 4, S21, both ports shorted

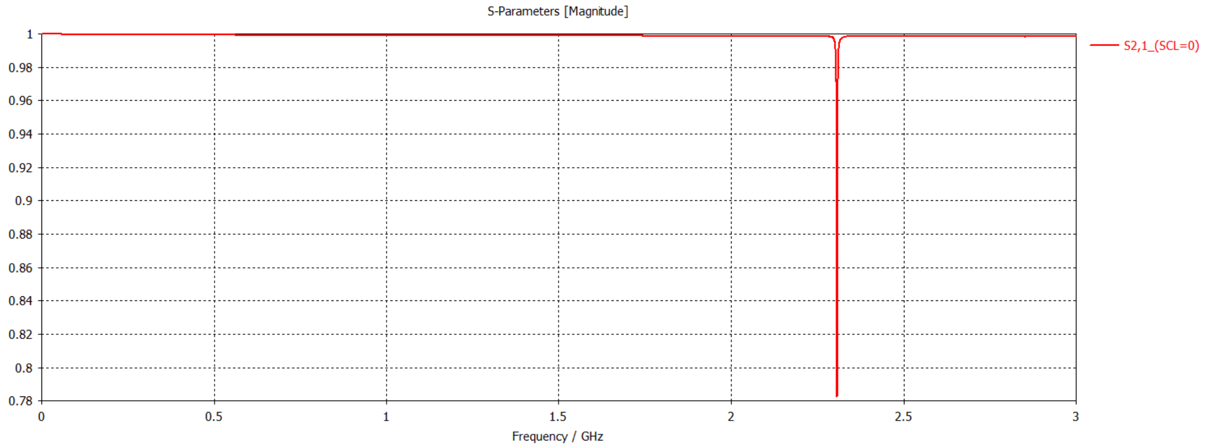



Figure 23: Case 5, S21, port 3 open, port 4 matched

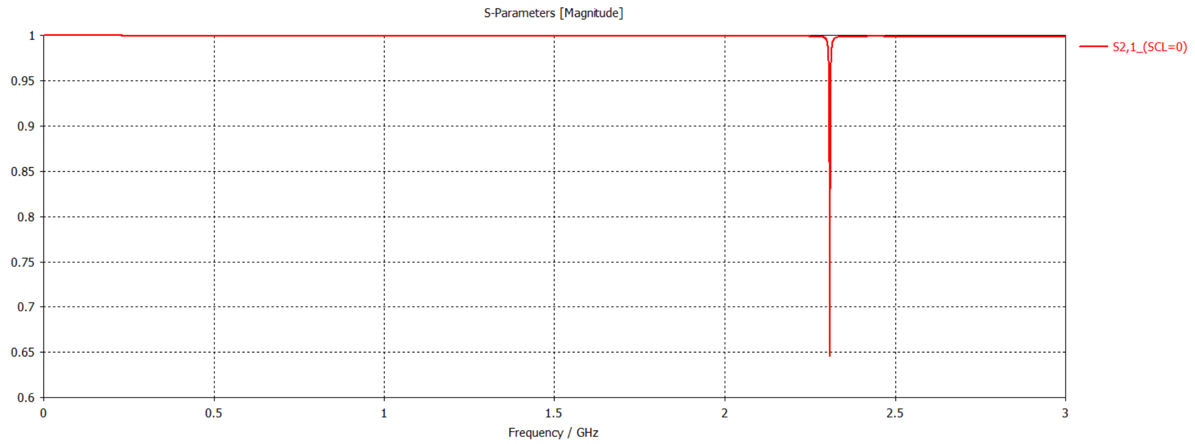



Figure 24: Case 6, S21, both ports open

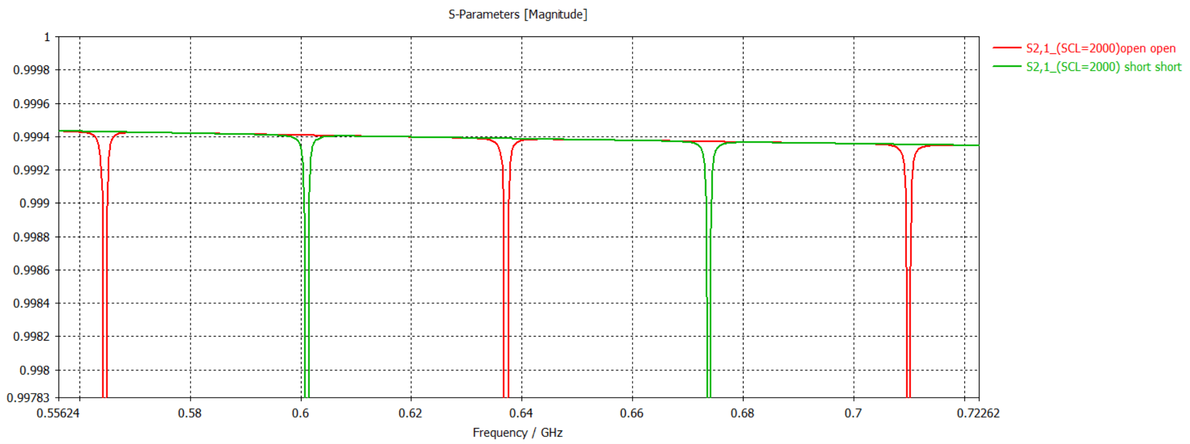



Figure 25: Cases 4 & 6 in comparison. The green spikes are located in between red spikes and vice versa

From the above figures we can see that when there is a short there is also a spike at the frequency of 0.65 GHz and when the cable is terminated with an open circuit there is a spike at the frequency of 2.3 GHz. If both cases are presented, also the two spikes can be found. If only one type of termination is simulated at both ports it just changes the amplitude of the spikes.

## 5.2. Simulations with attenuation

In this section we try to see how the attenuation of the cables interacts with the results. For the simulations we use a steady cable length of 2m and increase the attenuation of the cables by a factor of ten starting from 0.01 dB/m up to 10 dB/m. In the figure 26 and 27 the results for the shorted case are presented for every attenuation used. By increasing the attenuation the spikes become less sharp and start to lose amplitude. With attenuation of 10 dB/m you cannot see the spikes anymore.

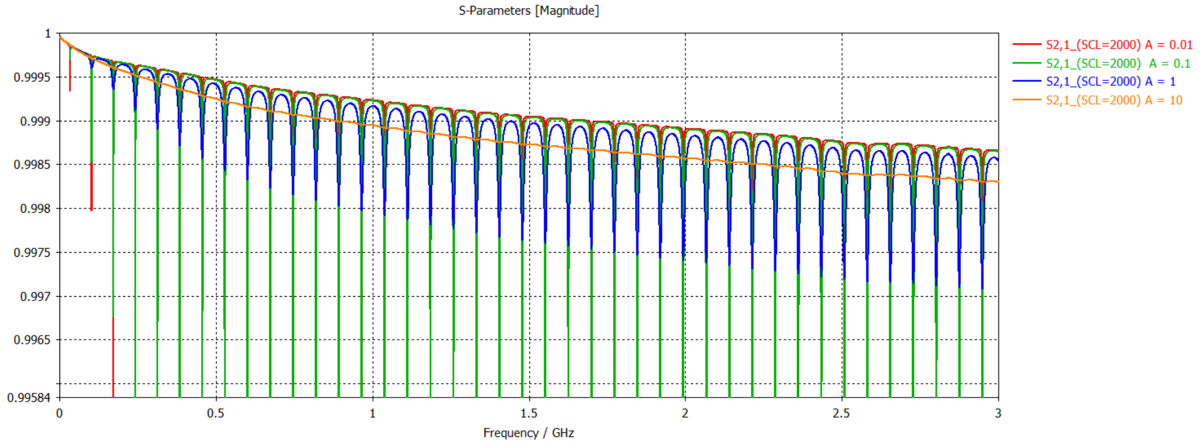



Figure 26: Different attenuations with a cable length of 2m and both ports shorted (case 4)

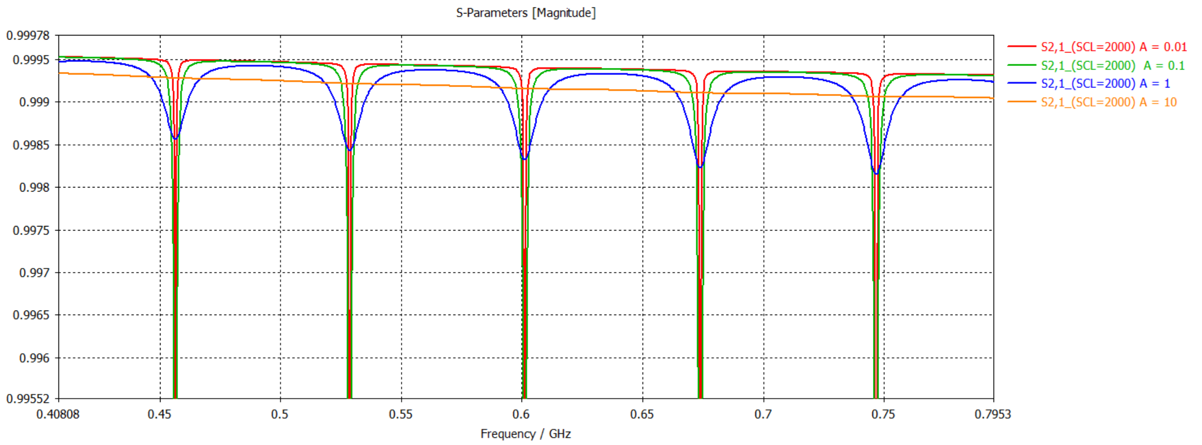



Figure 27: Close-up of the figure 26

The case 6 had similar results but with interleaved spikes. The shift is shown in the figure 28.

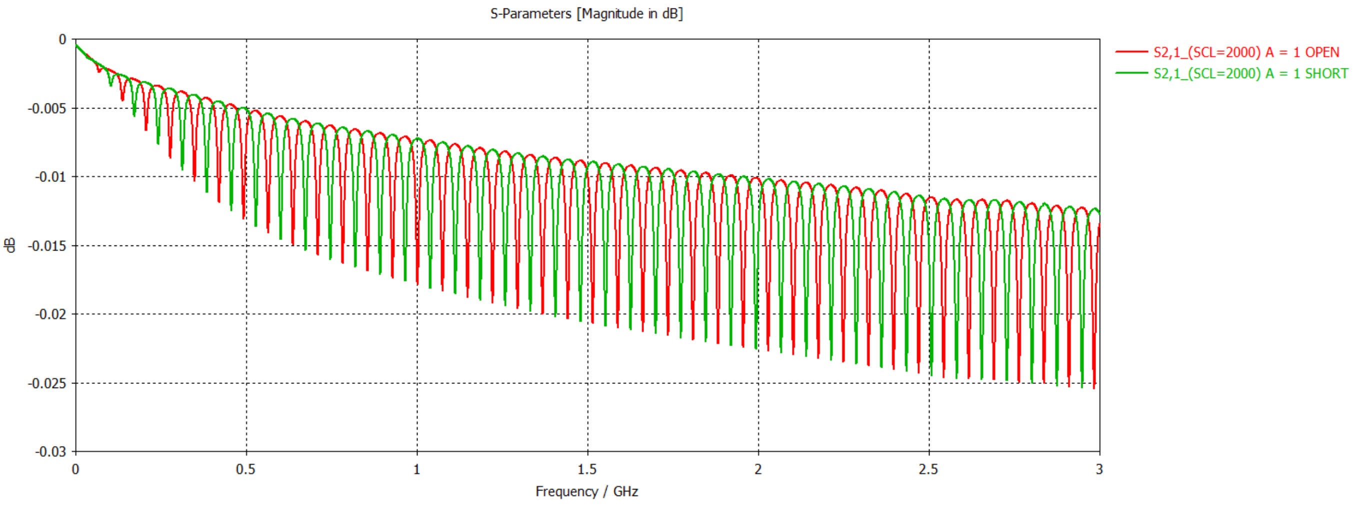



Figure 28: Comparison between case 4 and 6 with attenuation of 1 dB/m. The shift is still there.

# 6. Conclusions

The key point of this project was to study the effects of different kind of terminations at the BPMs and their effect on the beam. In order to achieve this a CST model was constructed and proven to be eligible to simulations with measurements. Different kind of simulations in the frequency domain and Wakefield solver were done and as a short conclusion it can be said that the aspect of different terminations with different cable lengths, attenuation and impedance (50 Ω has been used in all the calculations) can be modeled in CST to take into account the effect of the external circuits on the beam coupling impedance. The different termination produce a spike in a certain frequency which is dependent on what kind of a termination was used.

If the termination happens directly at the BPM it makes a strong difference which kind of termination it is. If it is a short a resonance with low frequency will be produced and if it is an open circuit a resonance with high frequency will be present instead. If we add cables of few meters length and the termination happens at the end of them, with both short and open there are resonances everywhere in the 0-3 GHz range. The resonances are interleaved with a distance of $\frac{\lambda}{2}$. When comparing both the shorted case and the open case the resonances are interleaved with a distance of $\frac{\lambda}{4}$ which is approximately 35 MHz (see fig. 28). With higher attenuation of the cables the resonances get smaller and almost vanish but that results in a higher signal power loss during normal operation. To summarize the results in one sentence: if the cables are pretty much lossless (very low attenuation), you have to be very careful with the terminations because of the reflections caused by the unmatched terminations.

There are still lots of questions that need to be answered:

- Why does the CST model not match the measured values in the frequency range of 0-0.7 GHz?

- What are the true effects on the beam?

- What if there are four BPMs (2 horizontal, 2 vertical)? Would it make a difference?

All in all this report gives an accurate description of my work in the past three months and hopefully it will be useful in the future in understanding the instabilities regarding the beam.

# REFERENCES

[1] E. Koukovini-Platia, H. Bartosik, G. Rumolo, C. Zannini, N.Biancacci (BE-ABP), M. Barnes, L. Sermeus (TE-ABT) and T. Levens BE-BI. “Identification of instability sources in PSB and LEIR”, BE-Newsletter Issue 24 December 2018. Available at:

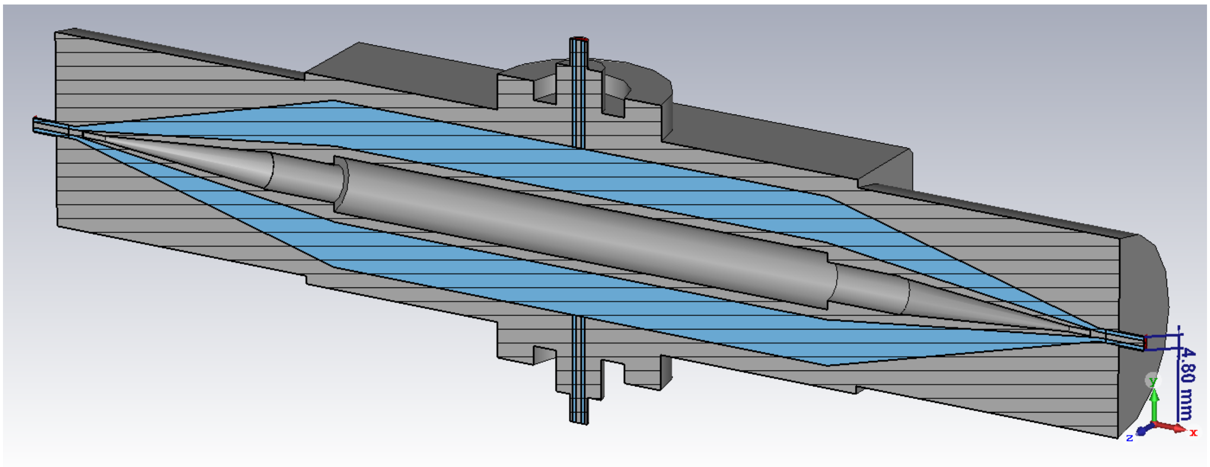
https://cds.cern.ch/record/2651040/files/BE-newsletter_2018_edition24.pdf

[2] C. Zannini, E. Koukovini-Platia, G. Rumolo “Beam coupling impedance of the PSB extraction kicker and its effect on transverse stability”, Impedance Meeting 16/11/2018. Available at:

https://indico.cern.ch/event/773228/contributions/3219667/attachments/1754421/2843873/PSB_EKFandHInstability.pdf

# APPENDIX

Simplified model:




The cable and adapter used at the first measurements: