# Characterisation of a Test Bench for the Development of an Electro-Optic Beam Position Monitor for the High-Luminosity Large Hadron Collider

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## Abstract

The project aimed to characterise a coaxial line setup required to test an Electro-Optic Beam Position Monitor (EOBPM) being developed for the High-Luminosity LHC. Experimental data were collected using a vector network analyser (VNA) and validated with electromagnetic simulations in CST.


## Motivation

The Large Hadron Collider (LHC) will be upgraded in 2025 to enhance its luminosity and discovery potential. To increase the luminosity crab cavities will be used. The Crab cavities will generate a transverse electric field that rotates the proton bunches, causing them to collide head on. This maximizes the beam overlap and therefore increases the collision probability. To optimise the crab cavities, high bandwidth diagnostic devices are being developed for intra-bunch measurements of transverse particle positions along a 1 ns bunch, based on the fast response of electro-optic crystals. These devises are referred to as electro-optic beam position monitors. The latest iteration of an electro optic pick up will be tested using the test bench characterised in this project.

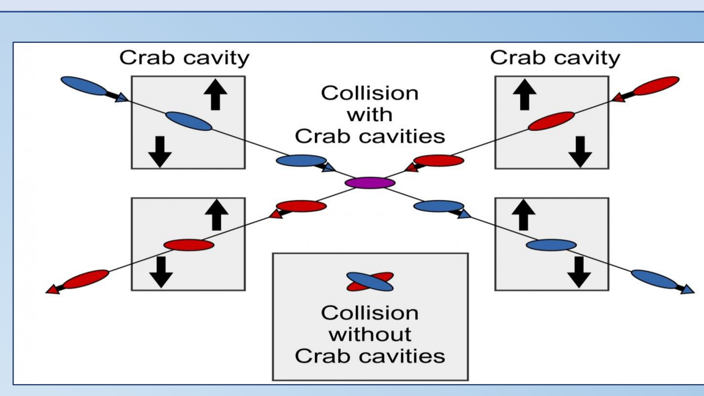


Figure 1: Diagram to show crabbing [1].

## Experimental Setup

The test bench is shown in figure 1, it is designed to act as a coaxial line with an impedance of 50Ω. It consists of a central cylindrical conductor, through which the signal is sent, and an outer cylindrical conductor that are separated by air which acts as the dielectric medium of a coaxial line. The outer cylinder has 2 flange holes on opposite sides. A frequency sweep sine wave was sent through the test Bench using a VNA. The signal transmission/reflection and the calculation of S-parameters is shown in figure 3. The VNA collects data in the frequency domain and transforms it to the time domain via inverse fast Fourier transform (IFFT)- this introduces discontinuities that can be reduced using a window function.

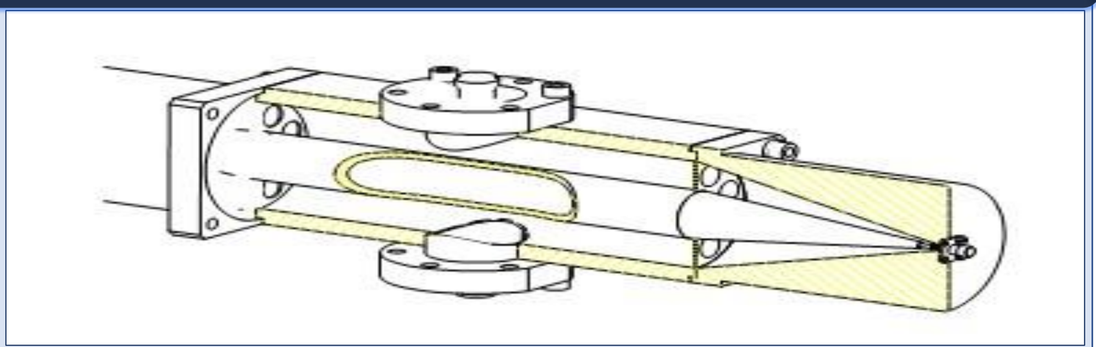

Figure 2: schematic diagram of the test bench [2].

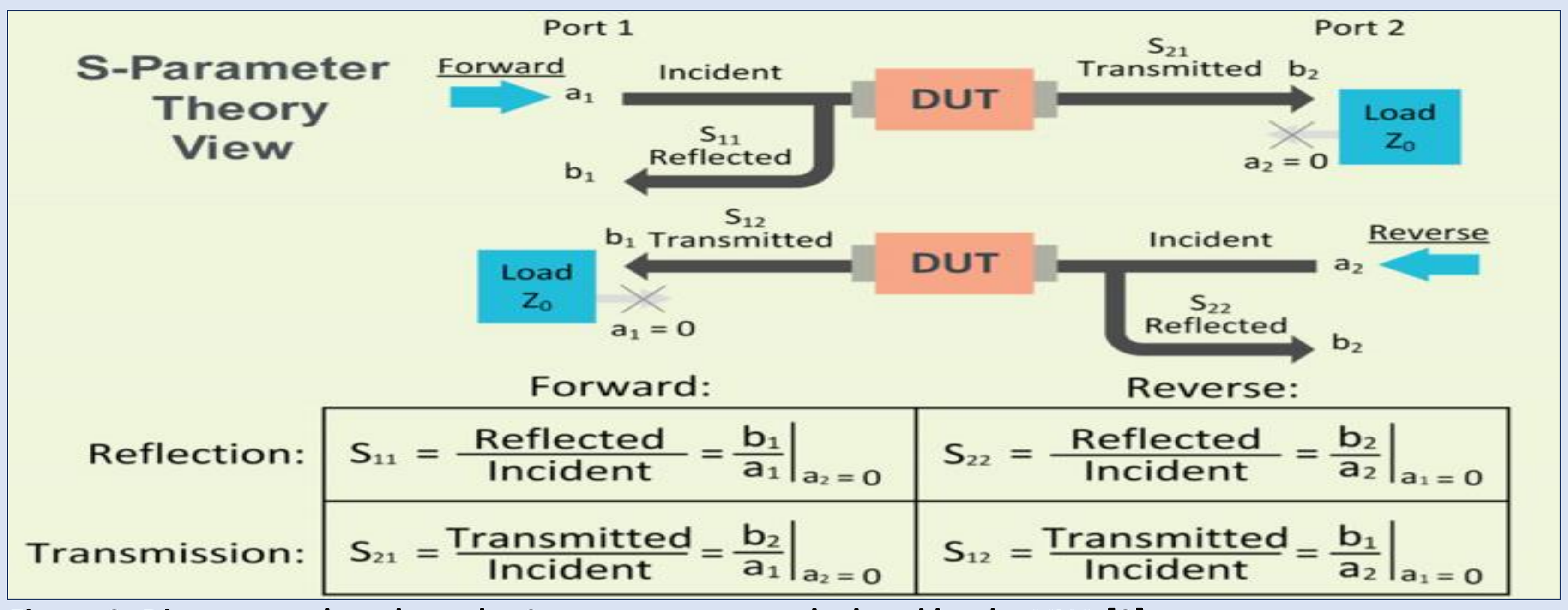


Figure 3: Diagram to show how the S-parameters are calculated by the VNA [3].

## Simulated Test Bench

Simulations were conducted using CST to verify ideas about the causes of transmission/ reflection peaks. The simulated test bench is shown in figure 4.

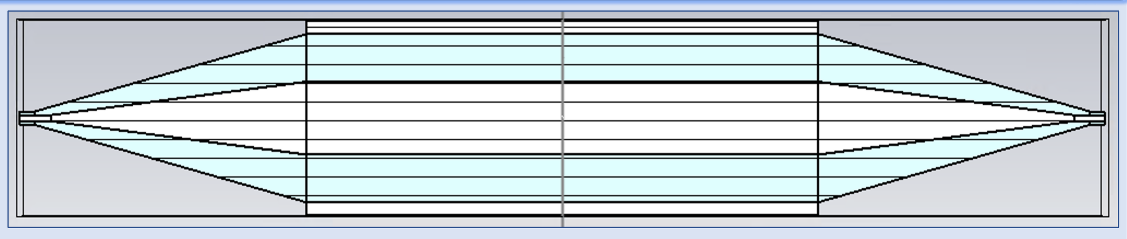

Figure 4: simulated test bench.

In order to provide this verification 4 central cylinder lengths were simulated: 198mm, 298mm, 398mm and 598mm. The results are shown in figure 5. A 100mm length increase resulted in: the port 2,1 signal peak shifting by 0.3ns and the 2nd port 1,1 signal peak shifting by 0.6ns. The first 2,1 signal peak was concluded to be due to the signal reaching the second port. The first 1,1 signal peak was concluded to be due to a reflection when the signal reaches port 1 and the second peak is thought to be due to the signal being reflected by port 2/ the second conical ending back to port 1.

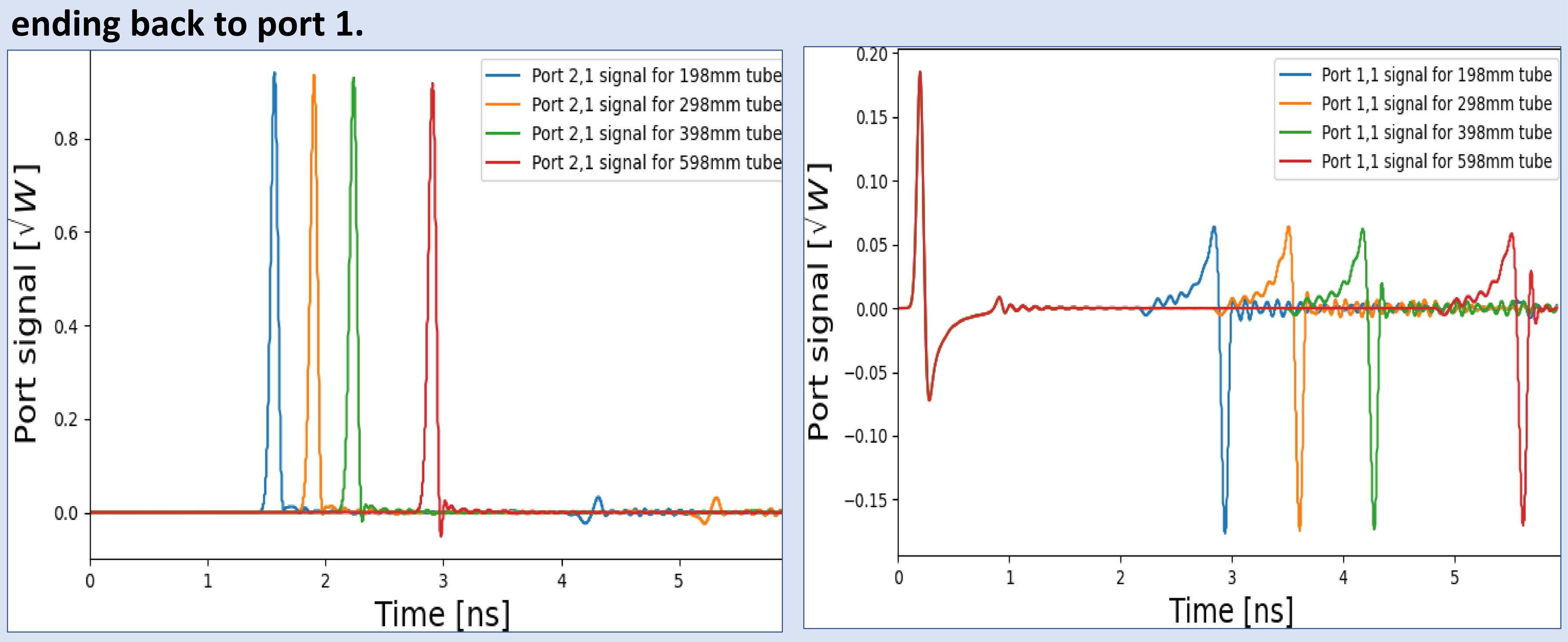


Figure 5: This figure shows the impact of changing the cylinder length on port signals 2,1 (left) and 1,1 (right) .

## Analysis of Experimental Data Collected with the VNA

- S21=S12, S11 and S22 showed positive correlation (shown by figures 6 and 7). This confirmed signal transmission was independent of direction, but reflection was not- likely due to manufacturing differences in the ends of the test bench.
- Changing the flange radius had minimal effect on signal transmission (shown by figure 8), and the same was true for the presence of a pickup.
- It is necessary to apply a hamming window to reduce discontinuities introduced by the IFFT and that a time gate was a good way to isolate interesting parts of the signal (shown by figure 9).

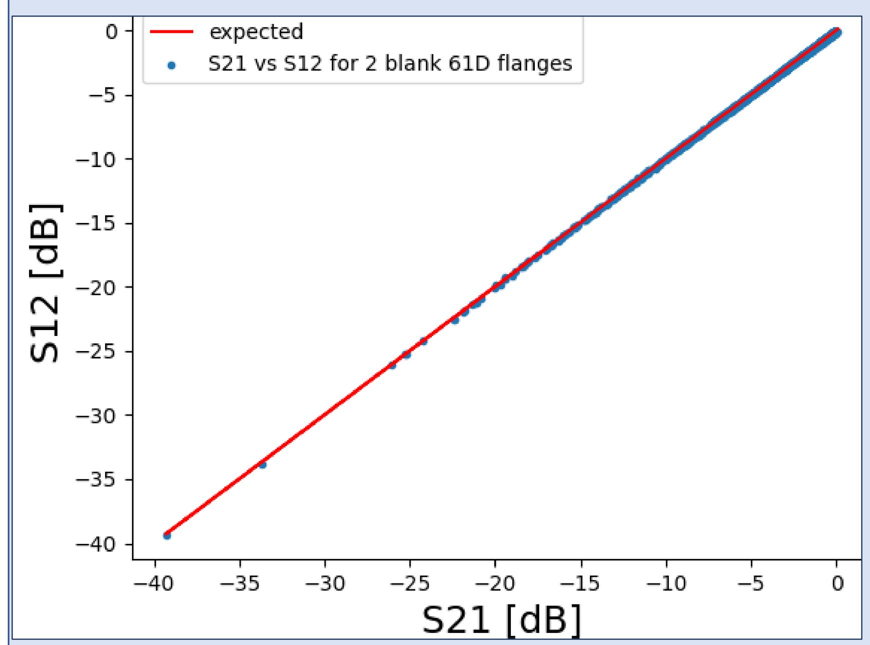


Figure 6: S12 vs S21.

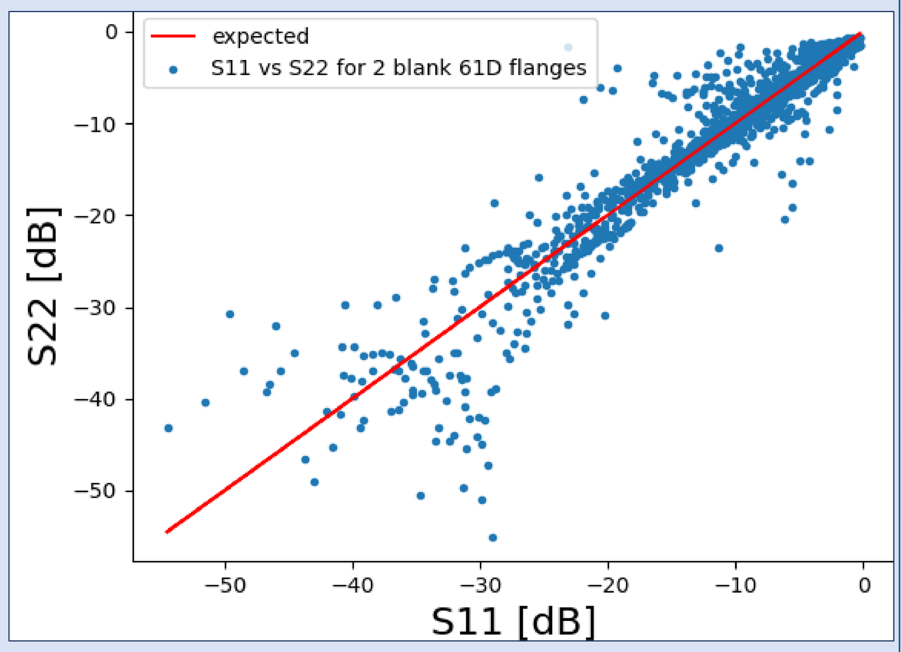


Figure 7: S22 vs S11.

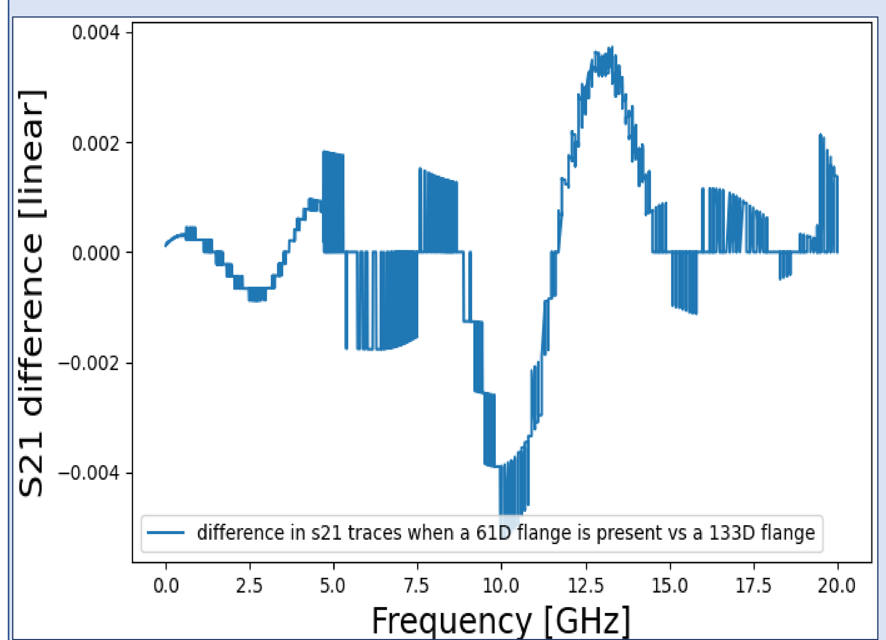


Figure 8: S21 difference due to changing flange radii.

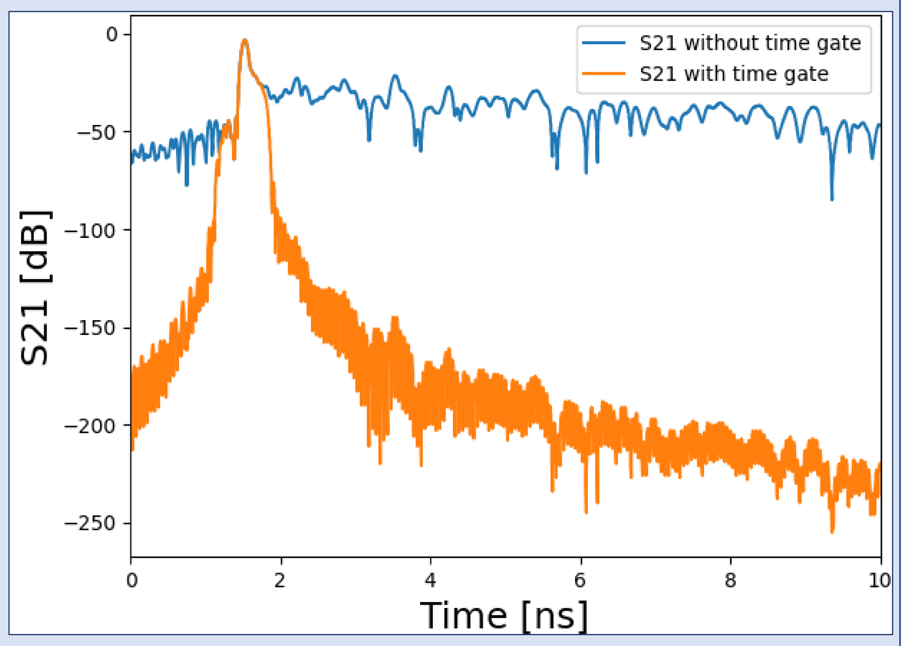


Figure 9: Shows the impact of applying a time gate.

## Comparison of Experimental and Simulated Transmission and Reflection Signals

The simulated 2,1 signal peak and the experimental S21 peak occurred at the same time stamp as did the first 1,1 signal peak and the first S11 peak. Therefore, conclusions drawn from the simulated data are valid for these peaks in the experimental data. The second simulated 1,1 peak on the other hand is not present in the experimental data but small S11 peaks are present to either side of it which could be due to reflections from the second conical ending.

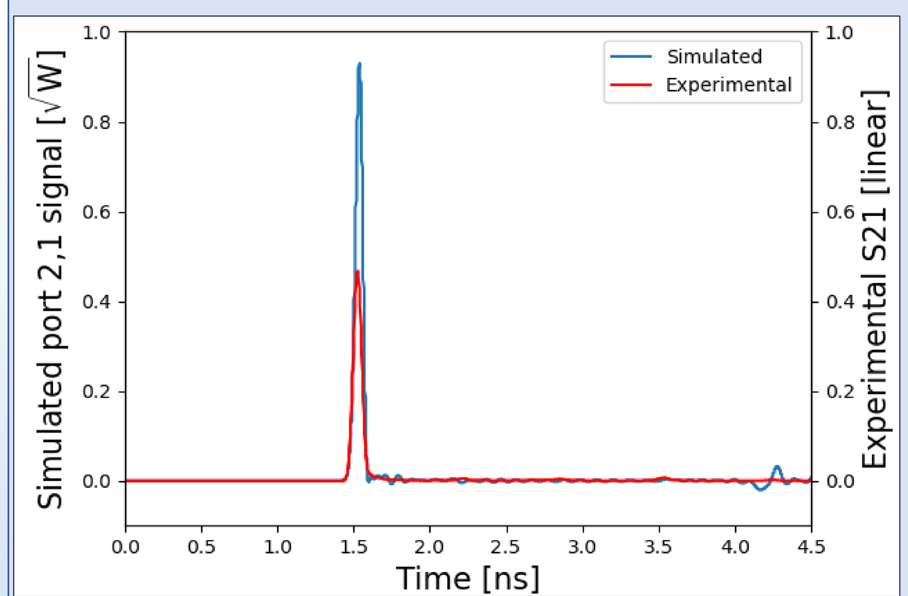


Figure 10: Comparison of simulated port 2,1 signal and experimental S21.

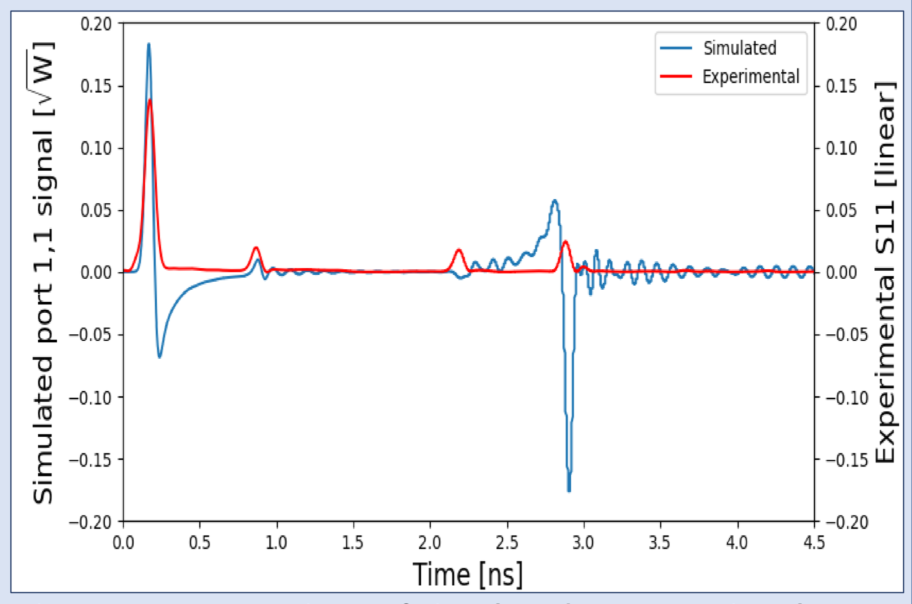


Figure 11: Comparison of simulated port 1,1 signal and experimental S11.

## Conclusions

The key experimental conclusions were: a Hamming window needed to be applied to reduce discontinuities introduced by the inverse fast Fourier transform (IFFT), a time gate was useful to isolate interesting parts of the signal, and minimal difference was caused to signal transmission due to changing flange radius or the presence of a pickup. From simulations it was seen that extending the test bench length by 100mm resulted in the port 2,1 signal peak shifting by 0.3ns and the 2nd port 1,1 signal peak shifting by 0.6ns. Therefore, it was concluded that the port 2,1 signal peak is due to the signal reaching port 2 as increasing the cylindrical section length increases the distance to the second port. For the port 1,1 signal it was concluded that the first large port 1,1 signal peak is due to a reflection when the signal first meets port 1, as it was unaffected by a length increase, and the second peaks are due to the signal being reflected from port 2/ the second conical ending back to port 1, as the time shift was double that of the port 2,1 peak and due to this signal being a reflection it would be affected by the length increase twice. Comparison between the experimental and simulated data showed that the simulated port 2,1 peak and experimental S21 peak occurred at the same time as did the first port 1,1 signal and experimental S11 peaks therefore the conclusions drawn from simulation about these were valid for the experimental data. The second port 1,1 peak on the other hand did not line up with the experimental data but two smaller S11 peaks occur to either side of the simulated peak which could be due to reflections from the conical ending or second port.

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References:
1 "Crab cavities: colliding protons head-on", CERN,https://home.cern/news/news/accelerators/crab-cavities-colliding-protons-head, accessed: 2/1/21
2."Update on RF bench tests", Alberto Arteche, Stephen Gibson, Alexey Lyapin, Abigail Hemming, EO-BPM Group Meeting, 27 November 2020
3."Introduction to VNA Basics", Tektronix, https://uk.tek.com/document/primer/introduction-vector-network-analyzers-basics, accessed: 27/2/21.