Longitudinal and Transverse Impedance Measurements and Simulations for ThomX

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BIMP-IJCLab(2020-2022)
DEPACC-LAL(2018-2020)

Outline

1.Introduction to Accelerators and Collective Effects

2.Wakefield and Impedances

3.Studying The Wakefield and Impedance

3.Two examples

4.Conclusion

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- How we achieved expected performance in accelerator?
- Why are the Collective effects are important?
- What is ThomX and what are the effects of collective effects on ThomX?

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- Different Kind of Impedances and Formalism
- The effect of the impedances
- The Goal of Impedance Study
- The methods of Defining the impedance on accelerators

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- Impedance Simulations with CST and Parameters
- The Coaxial Wire Technique and Experimental Setup
- Different Kind of Impedances and Measurements

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- The Coaxial Wire Technique and Experimental Setup
- Different Kind of Impedances and Measurements
- Bellow for two wire

3.Two examples

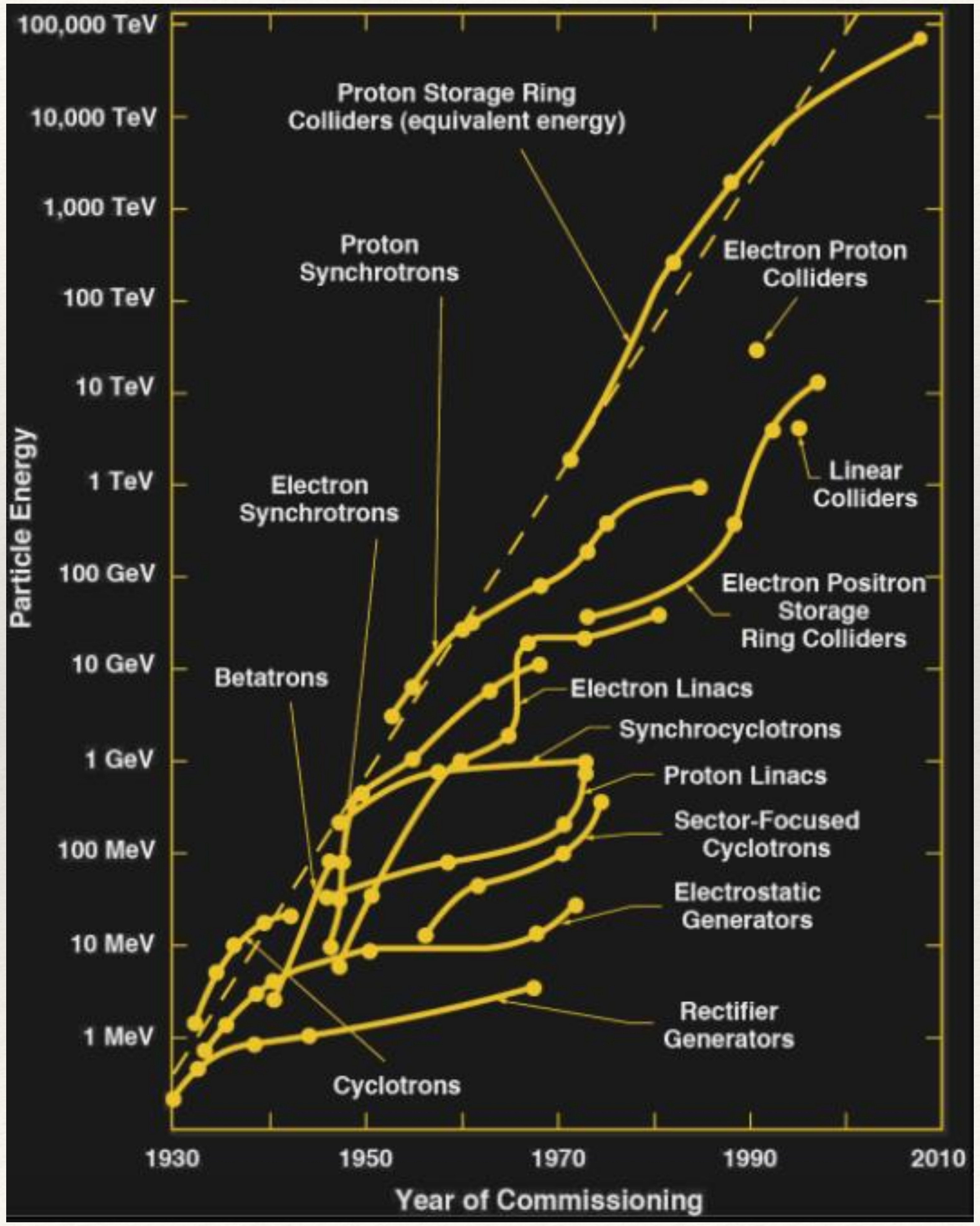
4.Conclusion

4

- FBT for moving wire

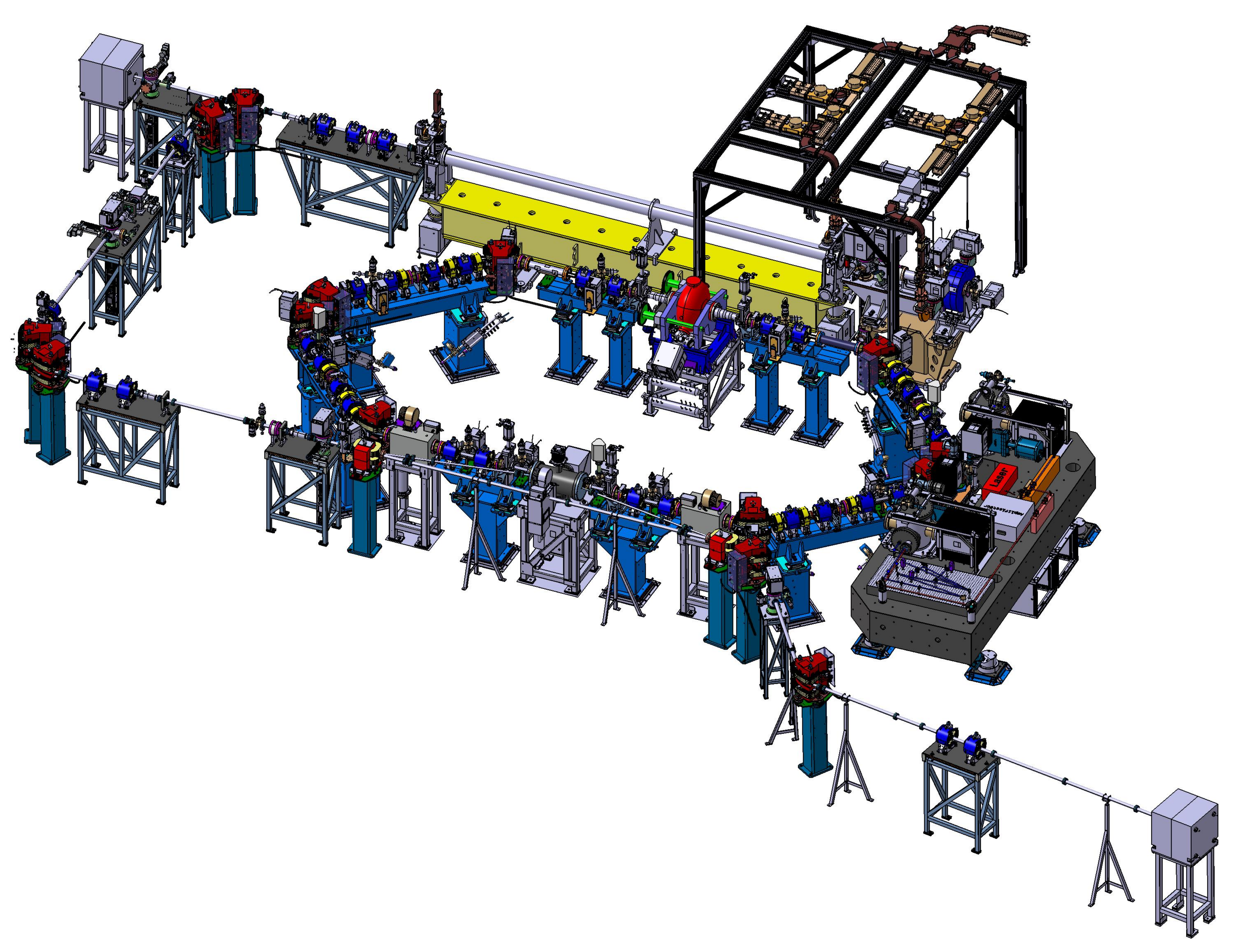
Introduction

- Nowadays the accelerators especially the light sources are used widely(e.g. physics research, medical applications, historical research etc.).
- Different usage needs different parameters(e.g energy, flux etc). For well-performed experiment the parameters should be achieved precisely.

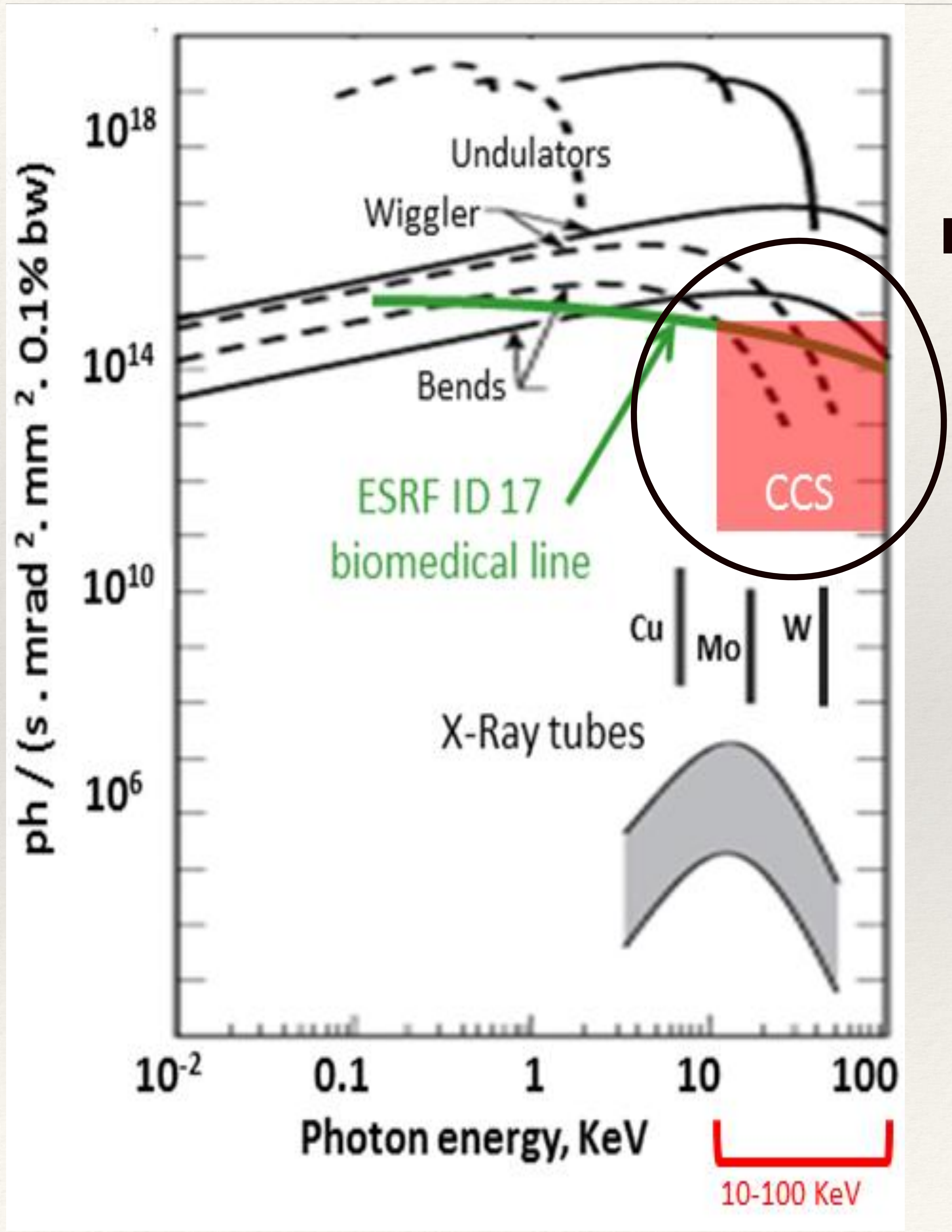


How we achieved expected performance in accelerator?

- Designing the accelerator for having the precise parameters in the exact places.
- The beam diagnostic (measuring the beam parameters in different place of accelerators) and feedback systems
- Studying the collective effects.



ThomX



ThomX X-Ray

Flux	10^{13} ph/sec
Brigthness	10^{11*}
Transv. beam size	70 µm
$E_{X\text{-ray}}$	30-90 KeV

Usage

Art History

Radiotherapy

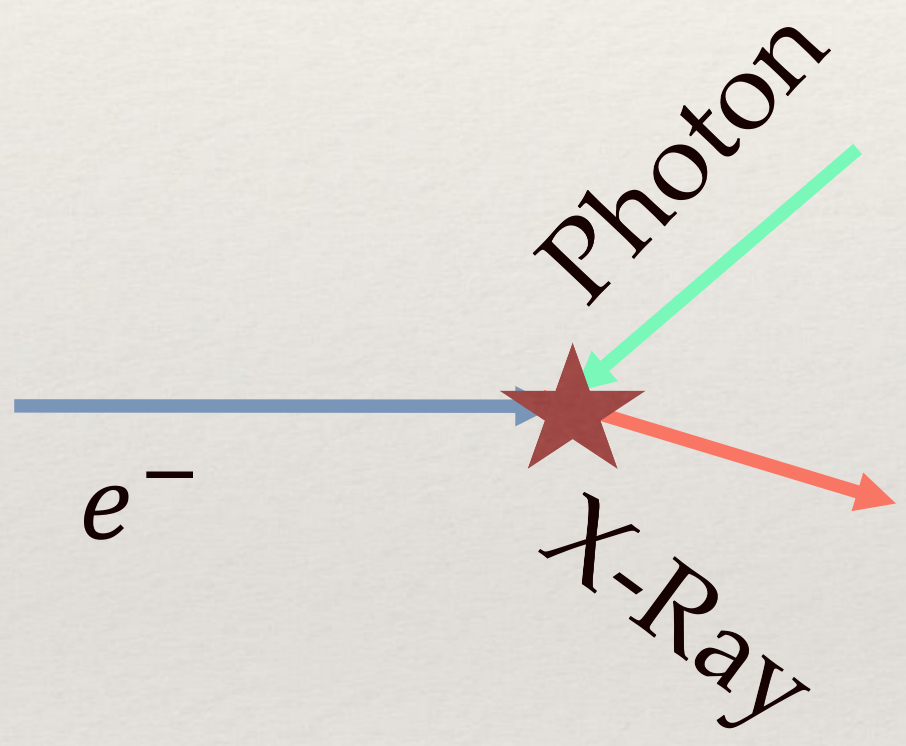
Imaging

Area of ThomX ~ 80 m^2
much smaller than the synchrotron light sources

$^*ph/sec/mm^2/0.1\%bw/mrad^2$

Compton Backscattering

$$E_{X-ray max} \approx 4\gamma^2 E_{photon}$$



50 MeV electrons → (ThomX) → 40 k times of the laser energy

- To maximizing the flux of the light sources we need:
  - High repetition rate
  - Small interaction angle
  - High charge

$$Flux = N_e N_{ph} f_{rep} cos\frac{\theta}{2}\frac{1}{\sqrt{\sigma_{ye}^2+\sigma_{yph}^2}\sqrt{(\sigma_{xe}^2+\sigma_{xph}^2)\cos^2\frac{\theta}{2}+(\sigma_{ze}^2+\sigma_{zph}^2)\sin^2\frac{\theta}{2}}}$$

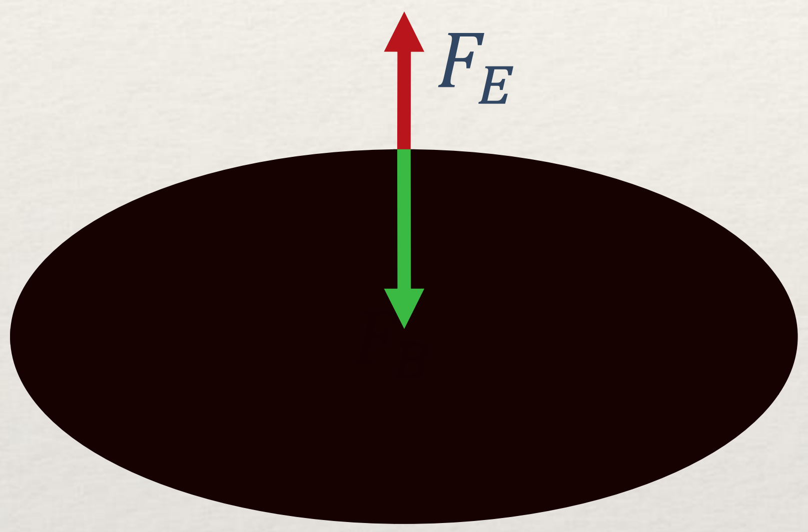
What is the collective effects?

- The Collective Effect term is used for defining the interaction of the particles with each other and surroundings.
- The Wakefield and Impedance formalism are generally used the collective effects.
- There are different type of collective effects which are act on accelerators.

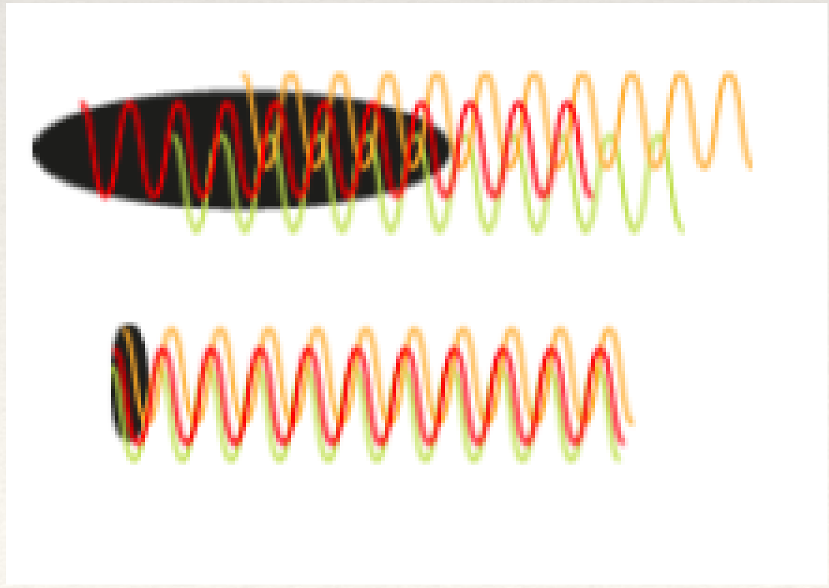
Collective Effects

Space Charge

Coulomb repulsion with the particles inside the beam



Coherent Synchrotron Radiation



Distortions

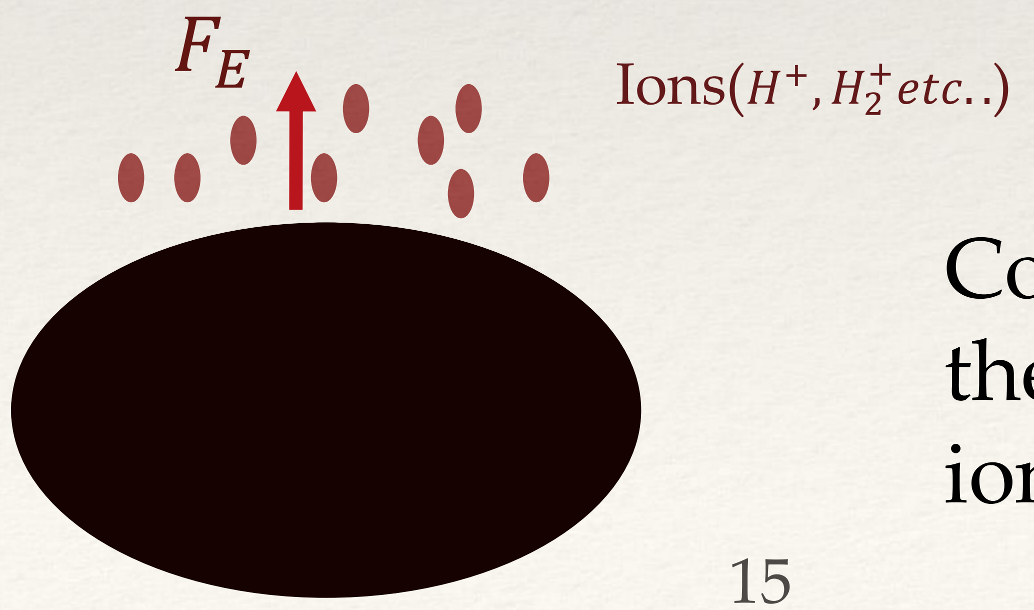
Emittance growth

Bunch oscillations

Instabilities

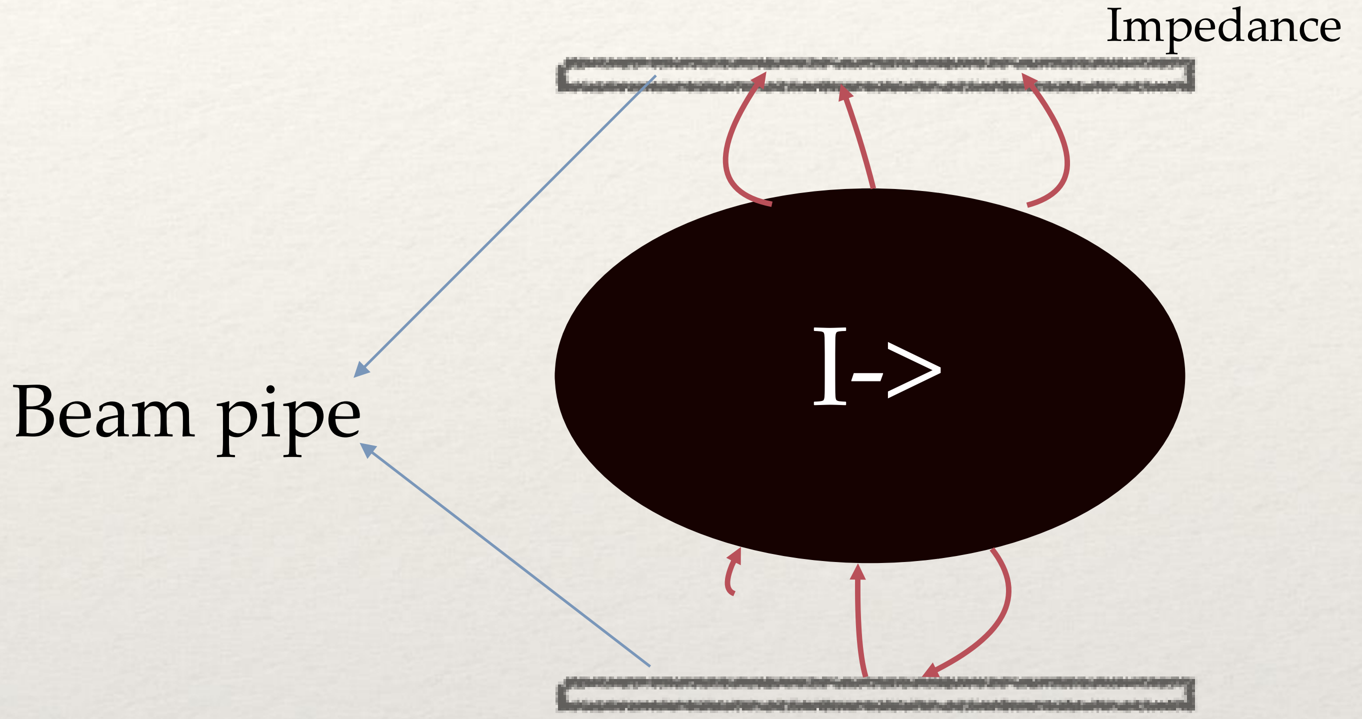
Beam losses

Beam-Ion Interaction



Coulomb attraction of the particles with the ions of residual gases

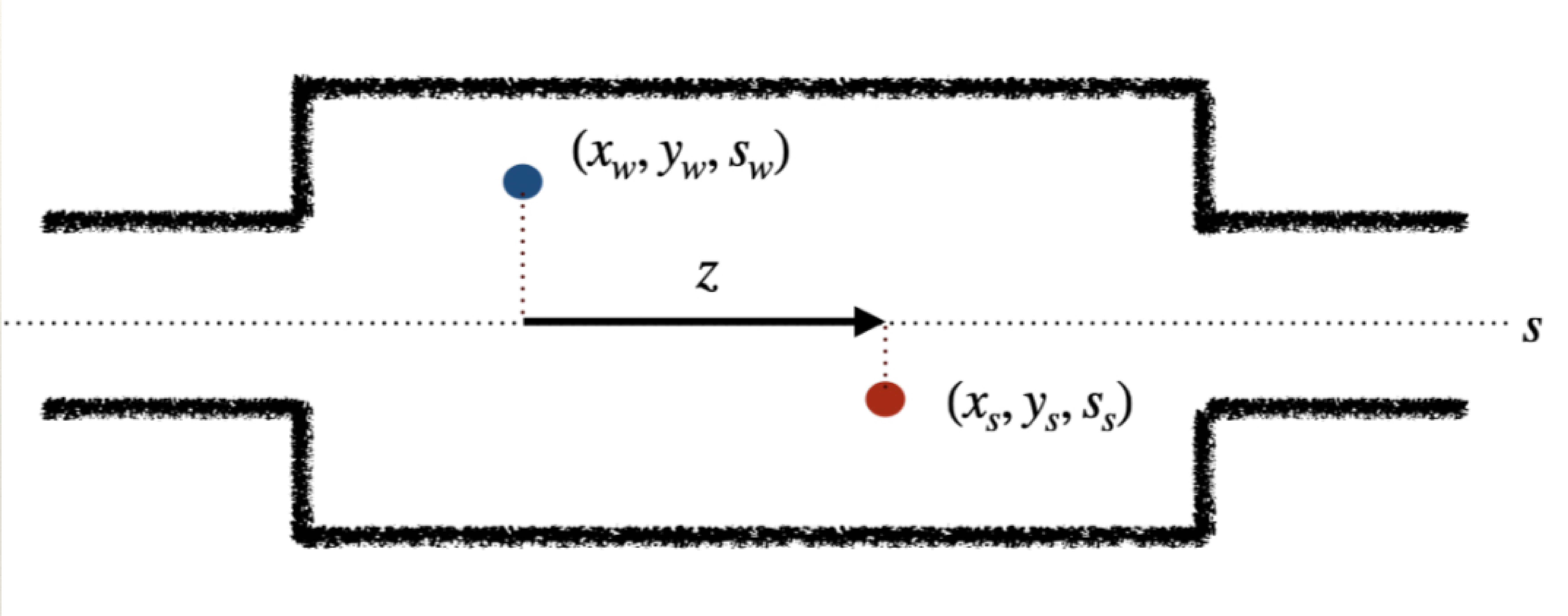
Beam Coupling Impedance



Intra beam Scattering

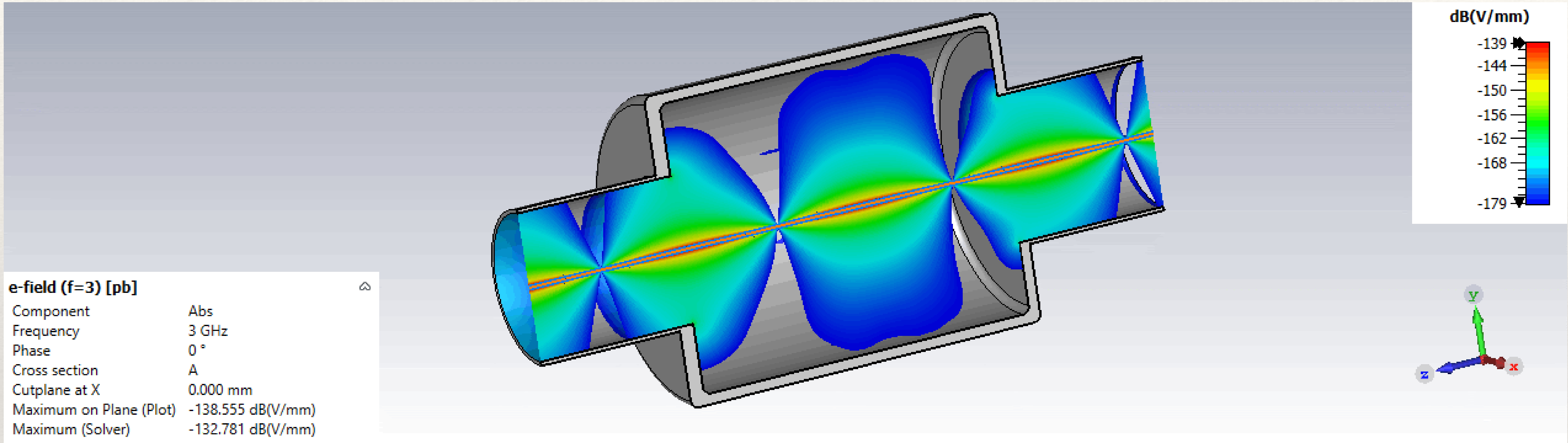
Collisions of the particles inside the beam change the colliding particles momentum by addition of multiple random small-angle scattering events.

Impedance



- When a particle beam passing through inside the beam pipe it can create electromagnetic fields behind it. These fields,which are called the wake fields, can have big effect on the beam dynamics for causing the energy lost. These fields can be define by wake potential or Impedance.

Impedance



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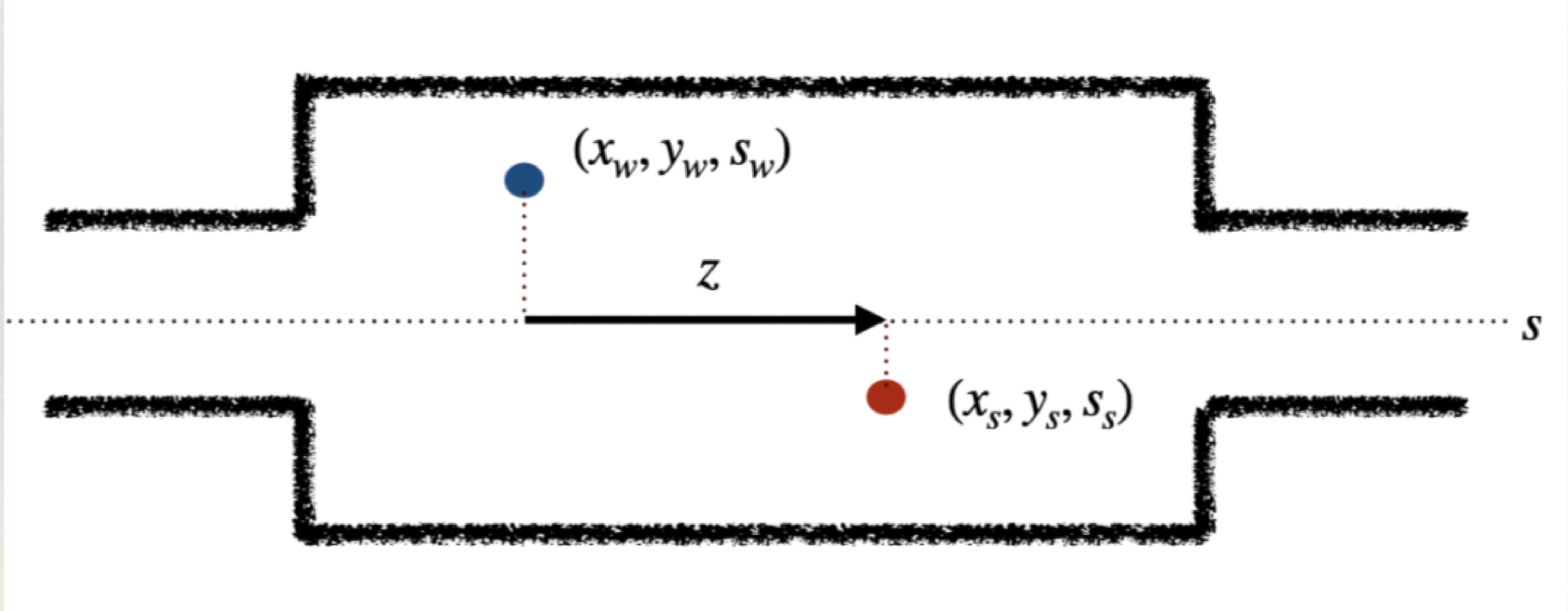
Longitudinal impedance

- The longitudinal wake function $W_{\|}$ is define the single source particle effect on the witness particle in the direction of motion:

$$W_{//} = \int_{-\infty}^{\infty} - dt \frac{1}{q} E_{//}(r_{source}, r_{witness}, vt - z, t)$$

- The effect can also be represented in the frequency domain by its impedance Z_L:

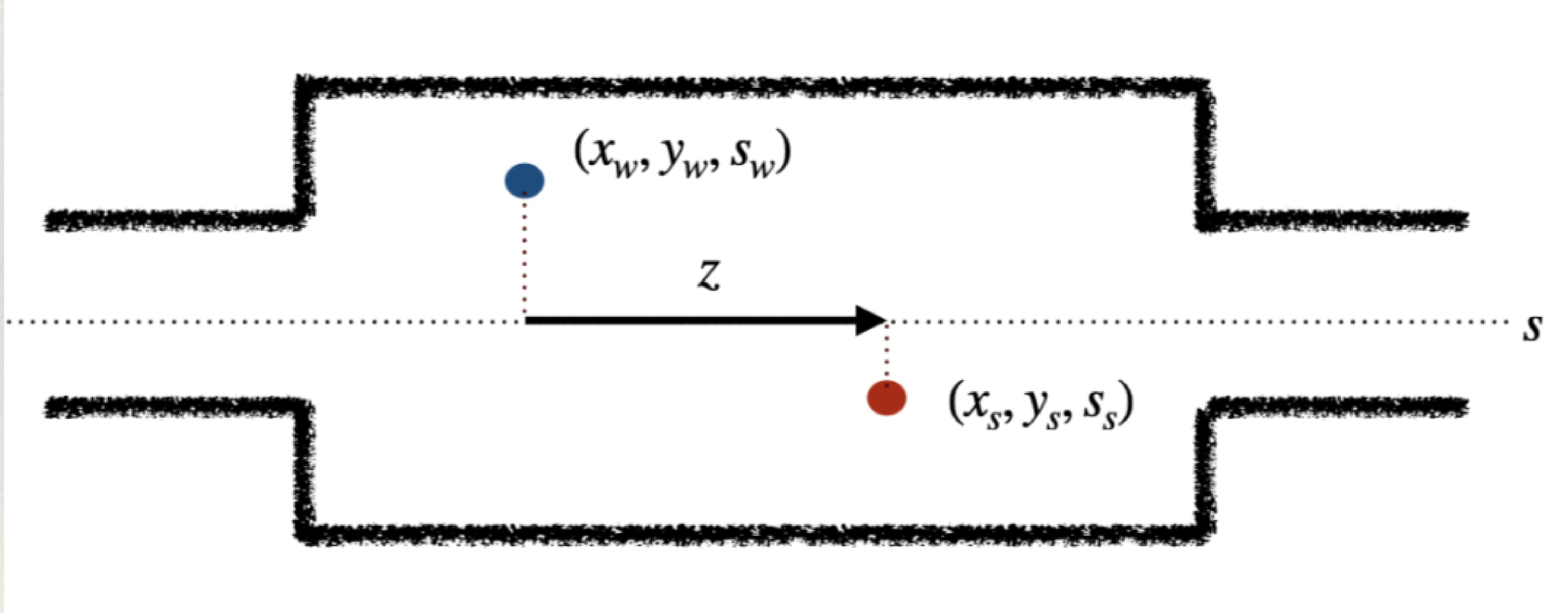


$$Z_L(u_s, u_t, z) = -\int_{-\infty}^{\infty} W_L(x_s, y_s, x_w, y_w, vt) e^{\frac{jwz}{v}} dz$$

Transverse impedance

- Also the wake function $W_\perp$ is used for defining the single source particle effect on the witness particle in the transverse planes:

$$W_\perp = -\frac{1}{q}\int_{-\infty}^{\infty} dt\left(E + \frac{v}{c}\times H\right)_\perp (r_{source}, r_{witness}, vt - z, t)$$

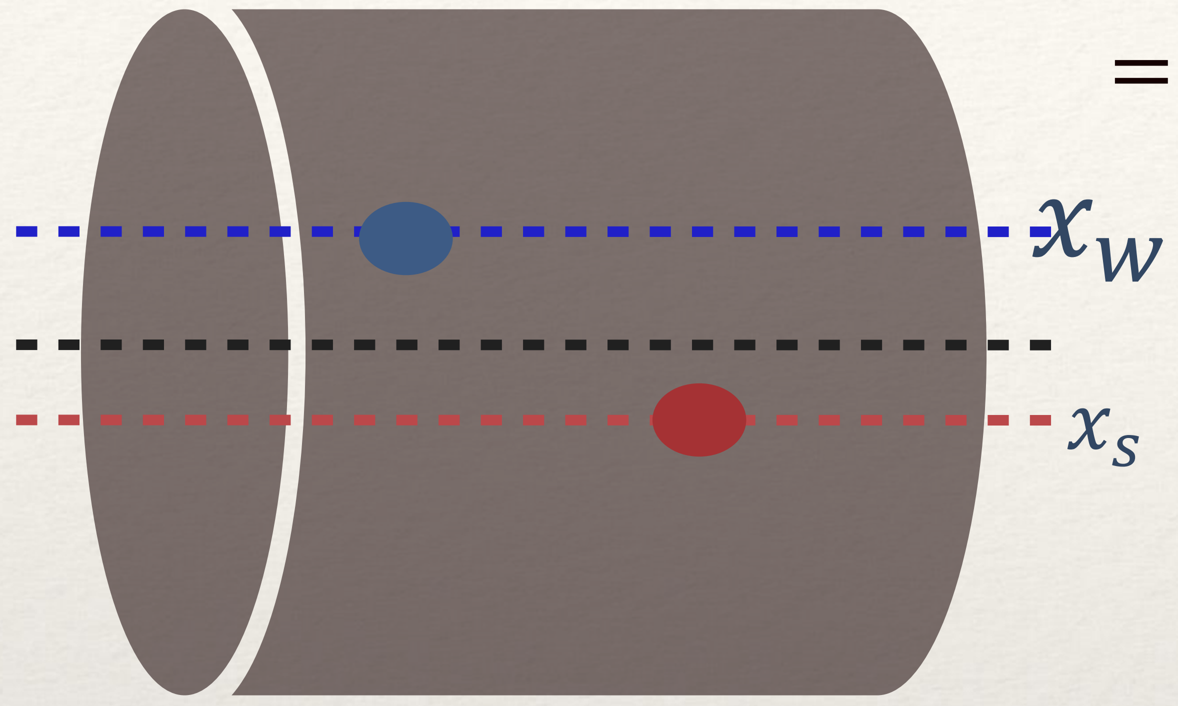


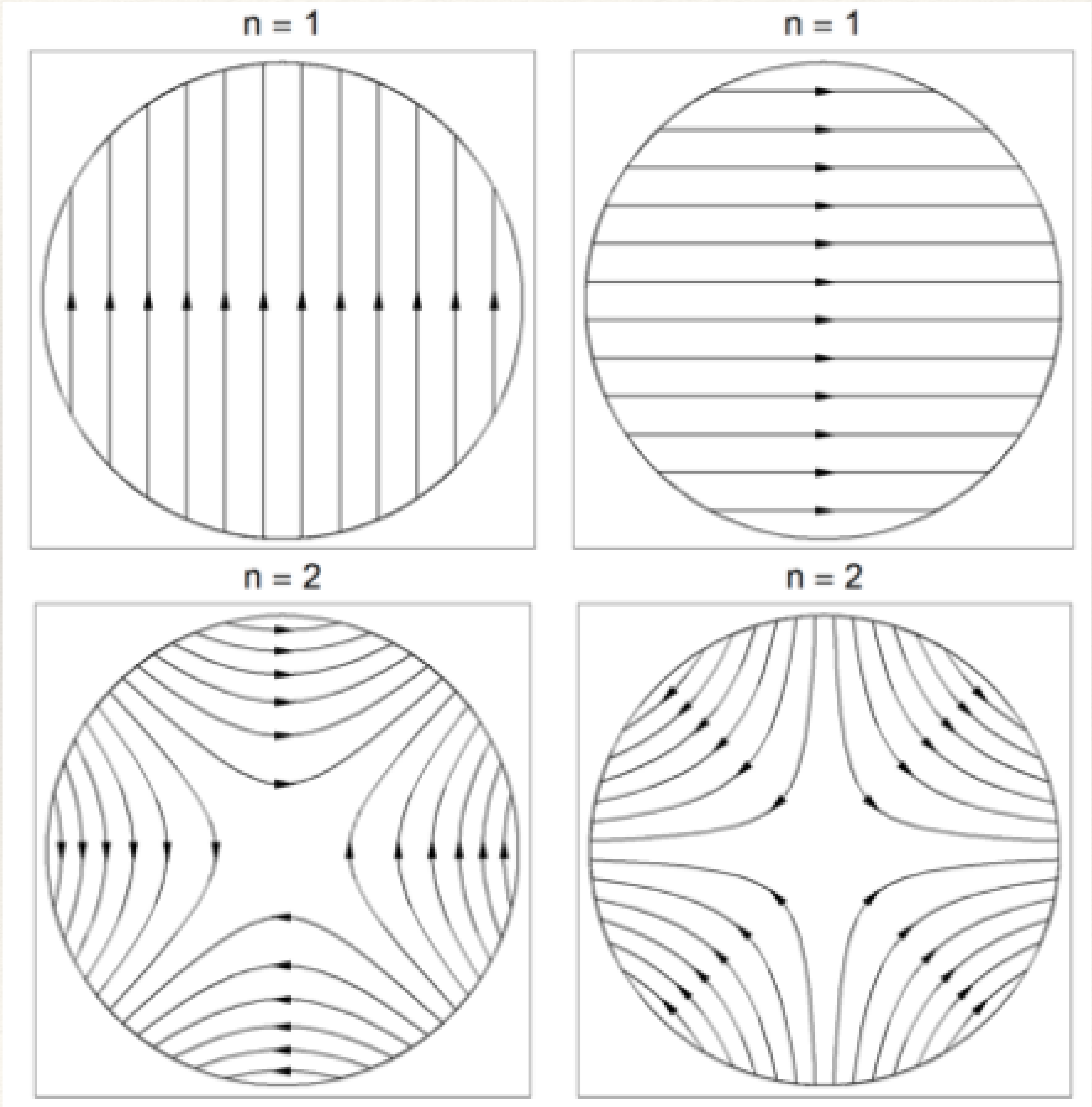
- The impedance becomes:

$$Z_\perp(\vec{u_s}, \vec{u_w}, z) = j\int_{-\infty}^{\infty} W_\perp(\vec{x_s}, \vec{x_w}, \vec{y_s}, \vec{y_w}, vt)e^{\frac{jwz}{v}} dz$$

Dipolar-Quadrupolar Impedance

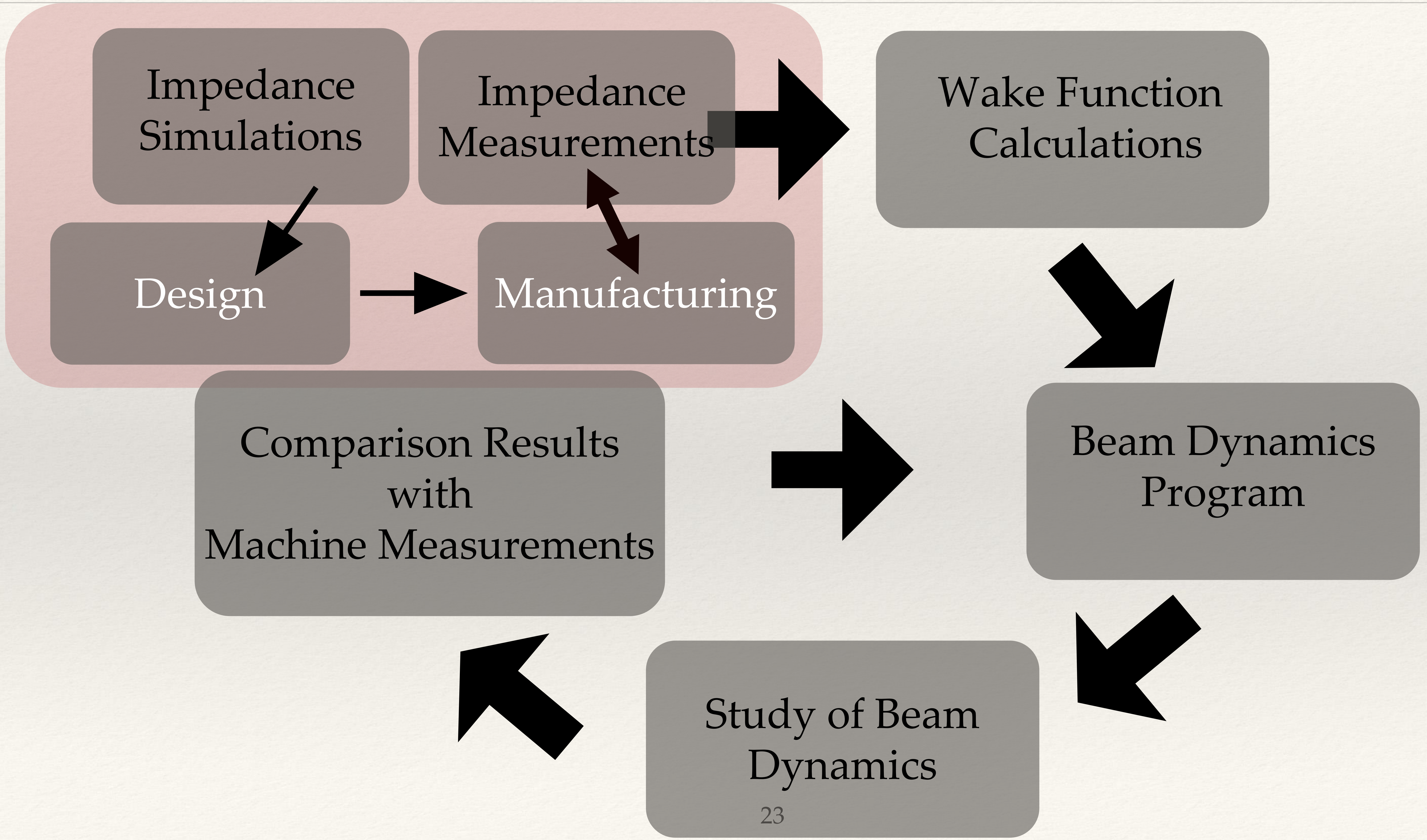
$$Z_x(x_s, x_w, f)$$
$$= Z_{x0}(f) + Z_{x,driv}(f)x_s + Z_{x,det}(f)x_w + O(x_s, x_w)$$





- The detuning(quadrupolar) kick depends only on the witness location(x_t). Incoherent effect -> detunes single particles
- The driving(dipolar) kick depends only on the source location(x_s).Coherent effect -> drives coherent instabilities

The Goal of Impedance Study



The Methods for Defining the Impedance

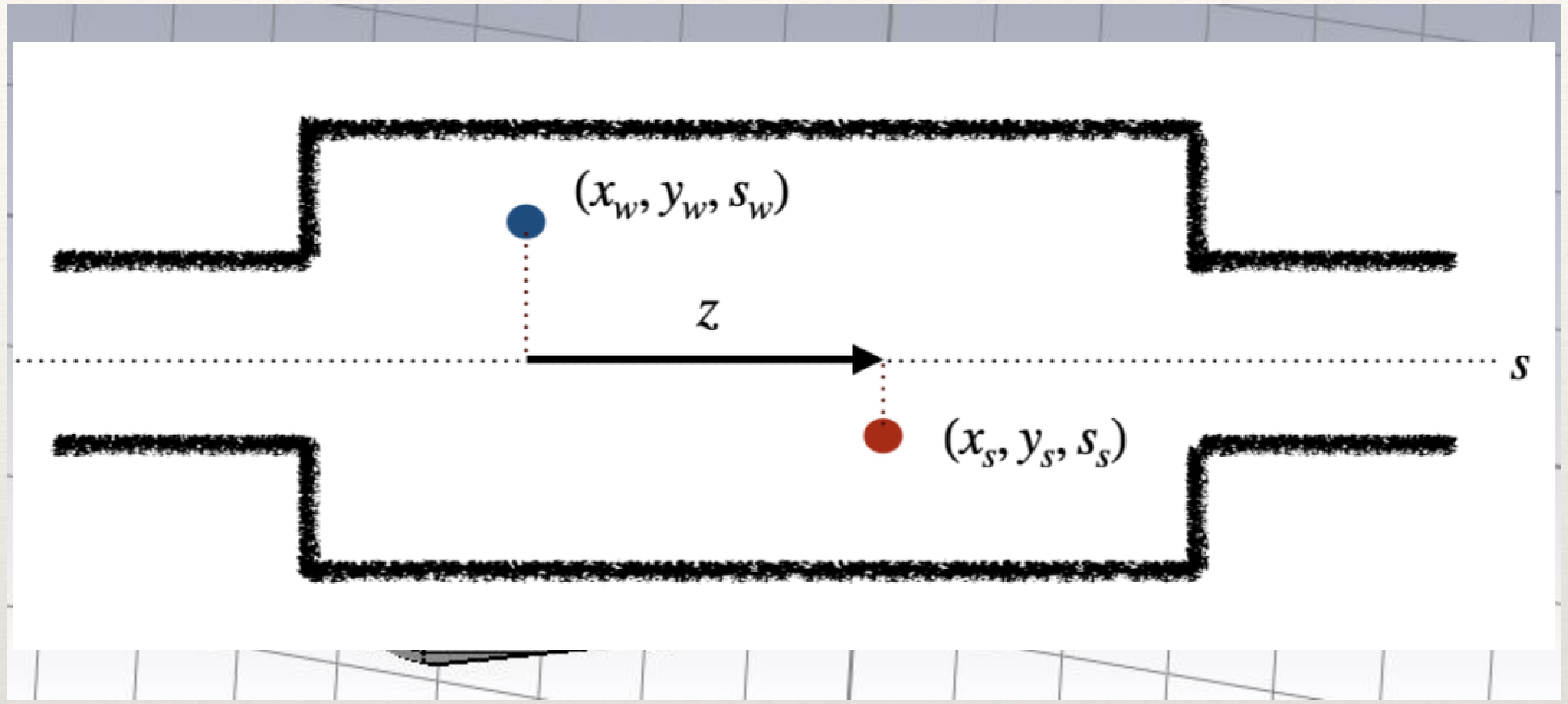
- Beam Measurements(after comissioning)
- Simulations(CST particle studio-Wakefield Solver)
- Wire Measurements
  - Longitudinal One Wire
  - Moving wire
  - Two wires
  - Wire Resonance Measurements

Simulations

- The main method used to design this model is 3D electromagnetic time domain simulations using the wakefield solver of CST Particle Studio
- It allows to study complex structures which are close to the geometry of the real objects.
- The standard output is the wake potential and the impedance is computed by Fourier Transform
- expected problems

CST Simulation example

- All simulations were performed with CST Particle Studio
- There are many parameters should be checked:
  - Number of Mesh cell
  - Mesh cell equilibrium ratio
  - Mesh cell per wavelength
  - Integration methods
- Many simulations were performed with step in out and rectangular cavity to optimizing the computational time , power and the accuracy.



# of mesh cell per wavelength	Total # of mesh cell	Simulation time(minute)
10	27.10^6	125
15	89.10^6	482
20	212.10^6	778
25	410.10^6	1035

Table : Simulation time of the step in-out cavity with respect to Parameters (others set to 1000 wavelength and 1.05 mesh equilibrium ratio).The simulations were performed with 6 cores,12 processors, 128 Gb RAM and Intel Xeon 2.10 GHz computer.

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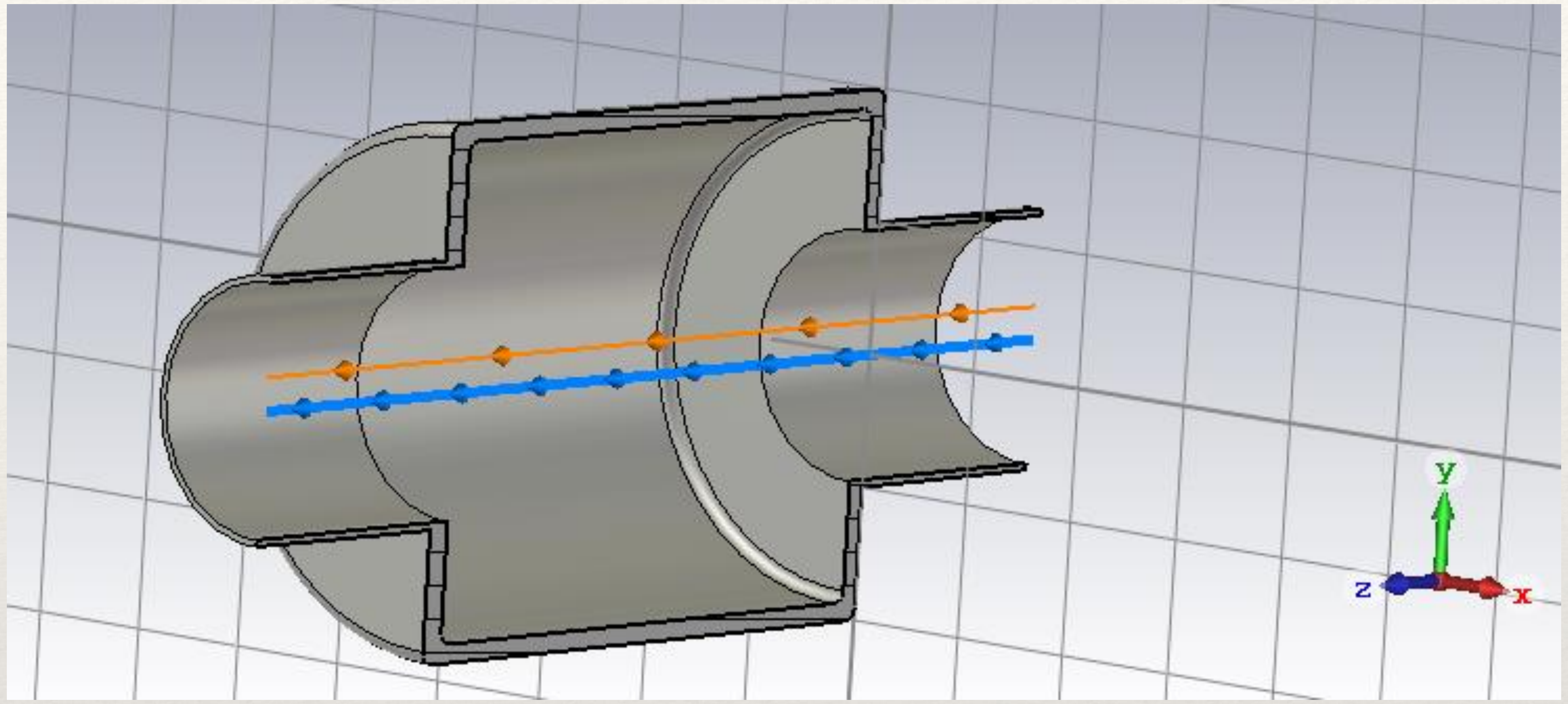

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Kick Factors

- The kick factors describes the transverse kick that a particle feel due to the impedance.

- Transverse case only effective impedance is the $Im[Z(w)]$ on the kick factor.

$$k_T = \frac{1}{\pi}\int_{-\infty}^{\infty} Im[Z_T(w)]|\tilde{\rho}(z)|^2 dz$$

where $|\tilde{\rho}(z)|^2$ is equal to spectral density ($h_l(w')$)

$$h_l(w) = \frac{w\sigma_z}{c}^{2l} e^{-\frac{w^2\sigma_z{}^2}{c^2}}$$

where σ_z is equal to standart deviation of the gaussian bunch.

Beam vs. Coaxial Cable

- The bunch interacts with a beam pipe in exactly the same way as a coaxial cable.

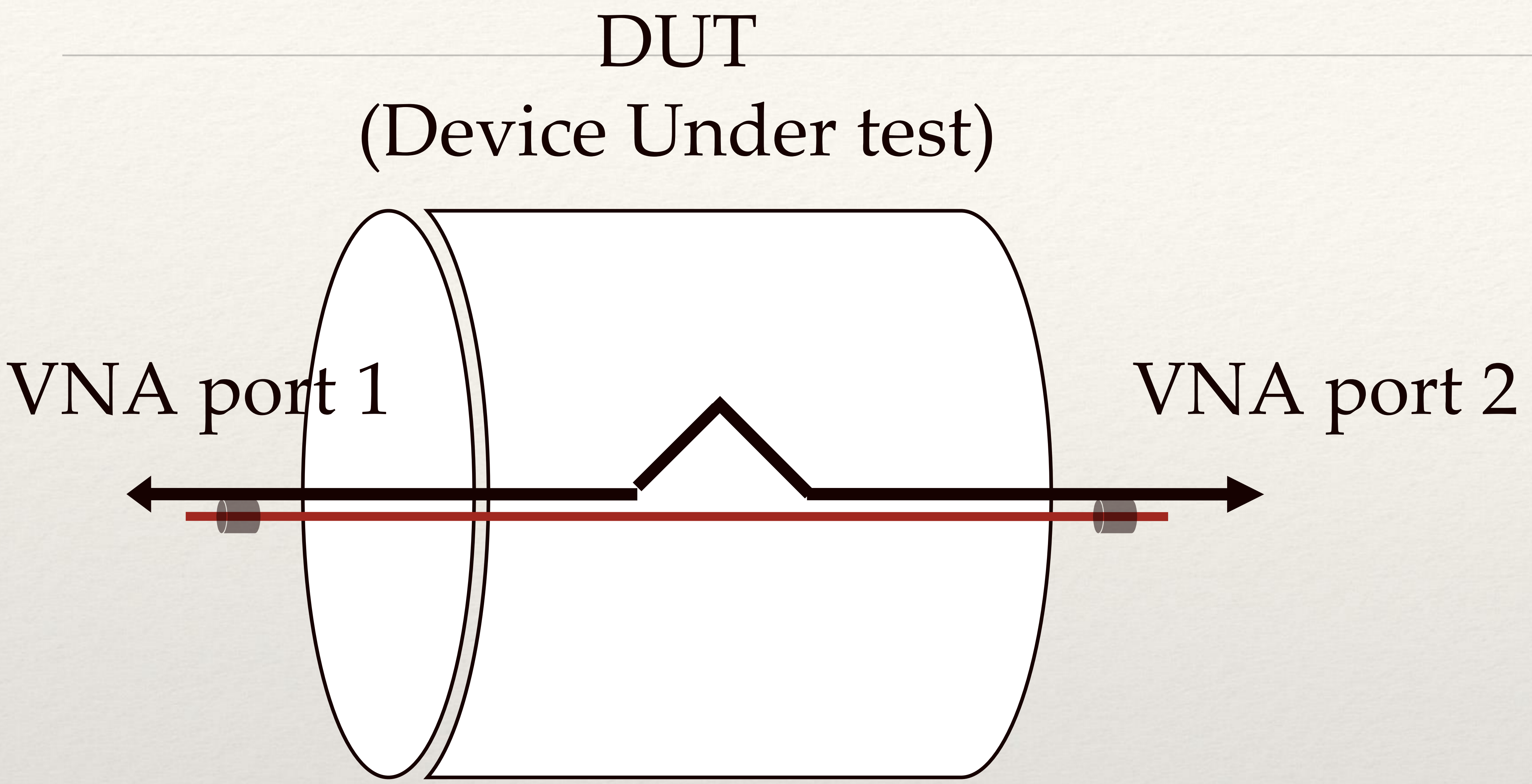
- Ultrarelativistic beam field

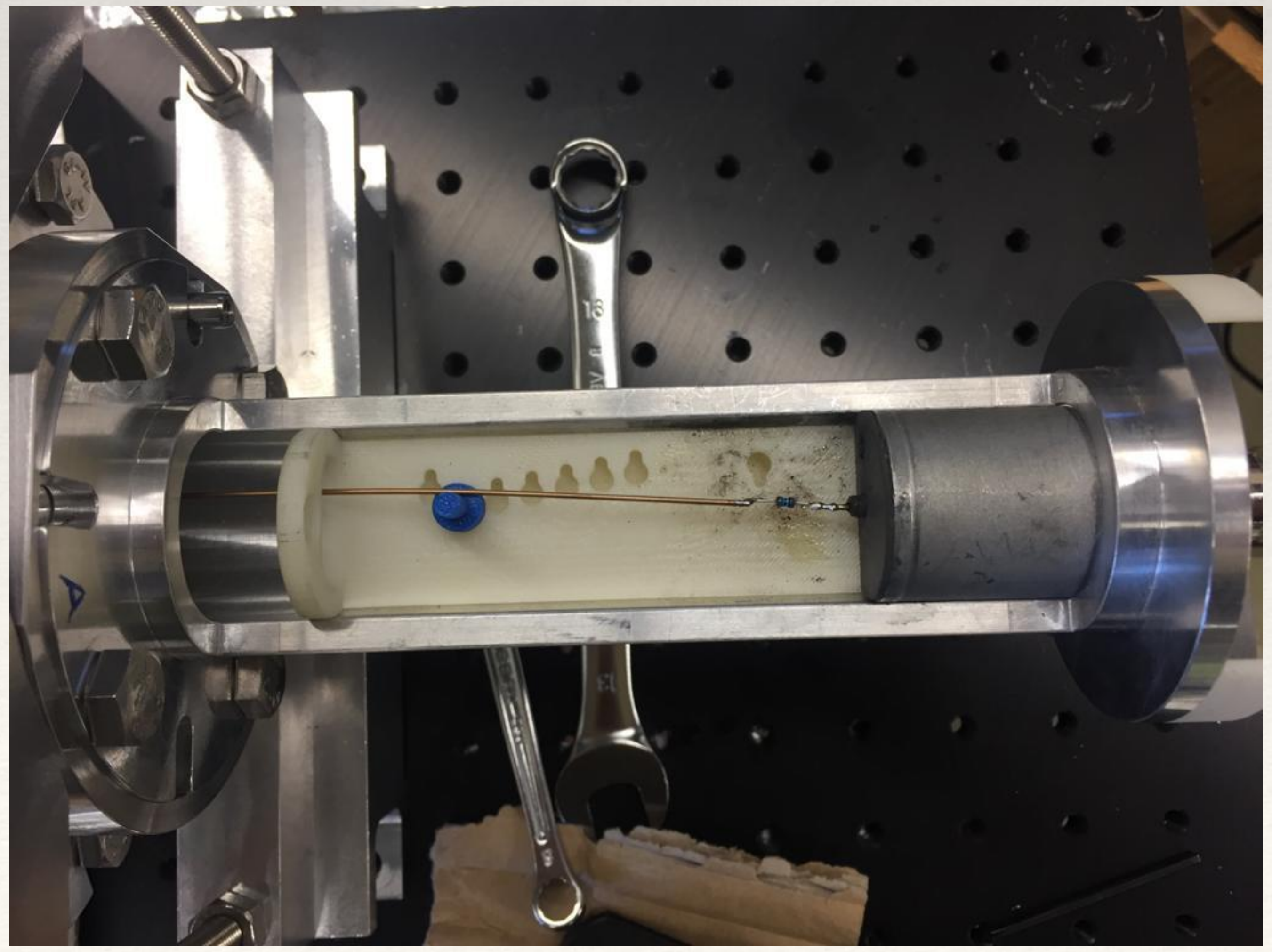
  - $E_r(r,w) = Z_0 H_\phi(r,w) = \frac{Z_0 q}{2\pi r} \exp(-j \frac{w}{c} z)$

- TEM mode coaxial wave guide

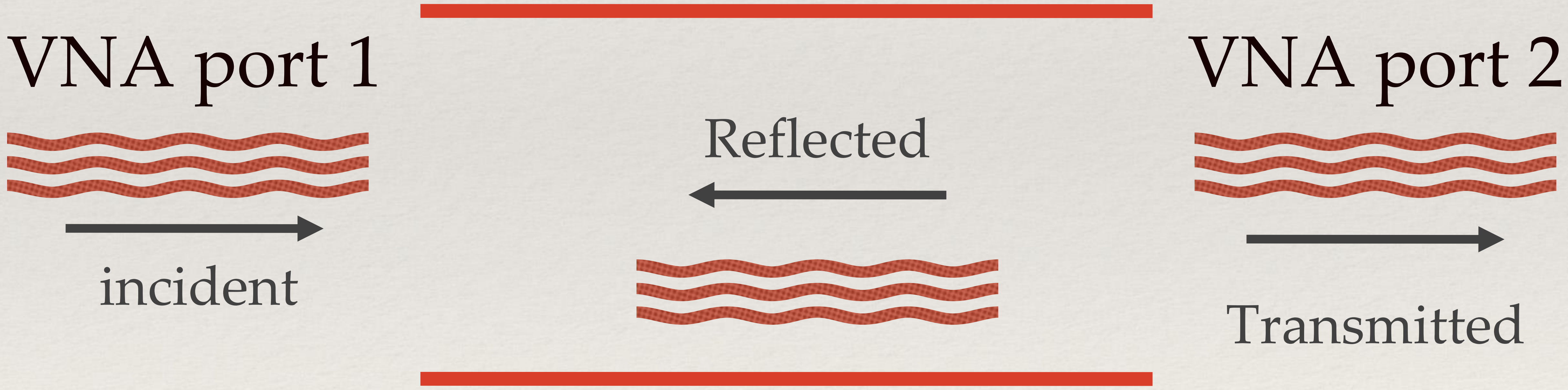
  - $E_r(r,w) = Z_0 H_\phi(r,w) = \frac{Z_0 q}{2\pi r} \exp(-j \frac{w}{c} z)$

Experimental Procedure

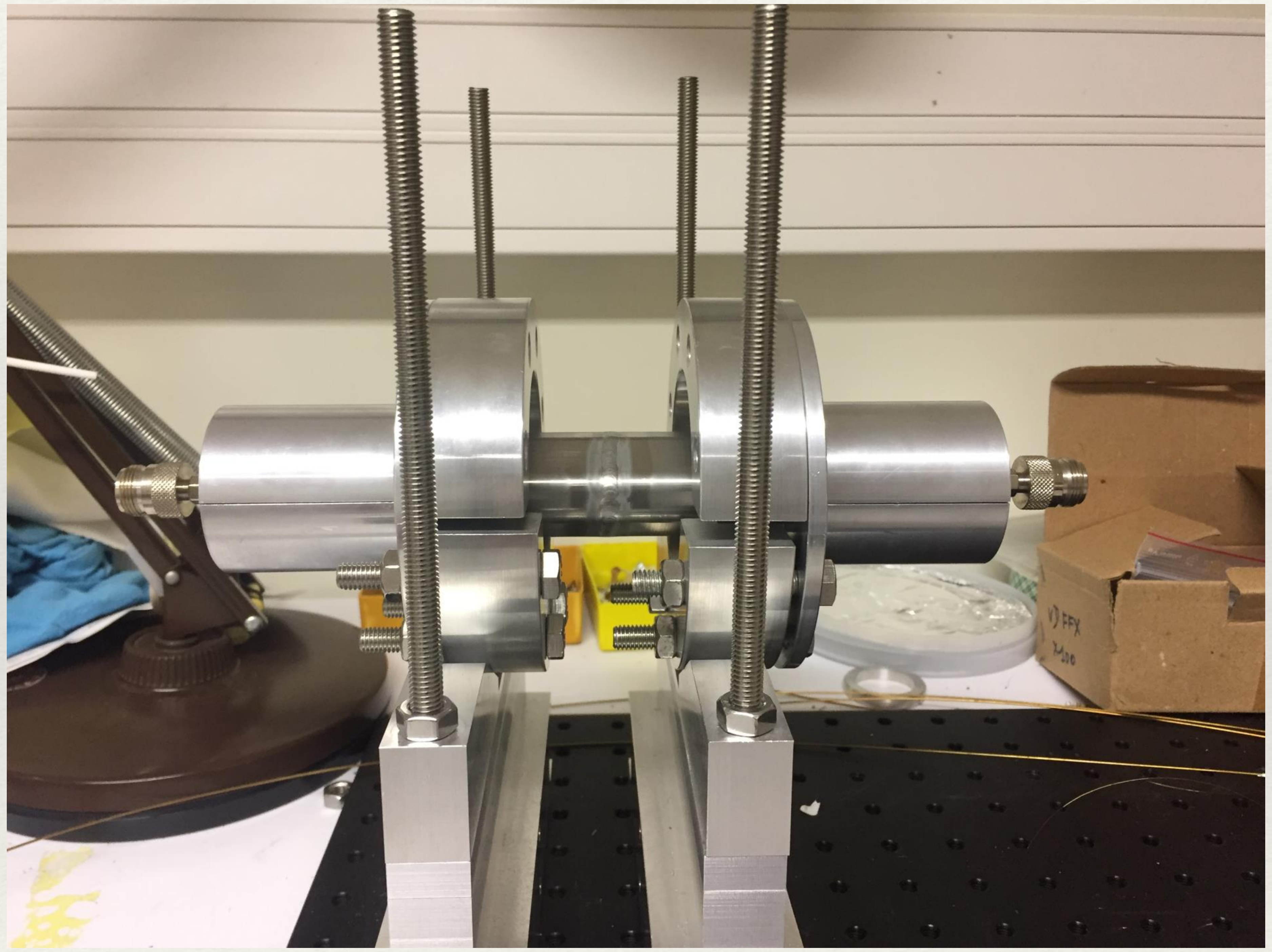




- The electromagnetic wave propagate through wire to VNA.

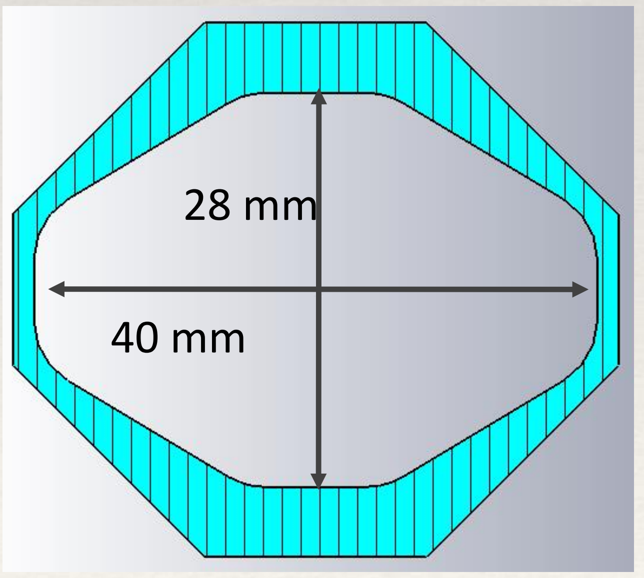


Reference Piece



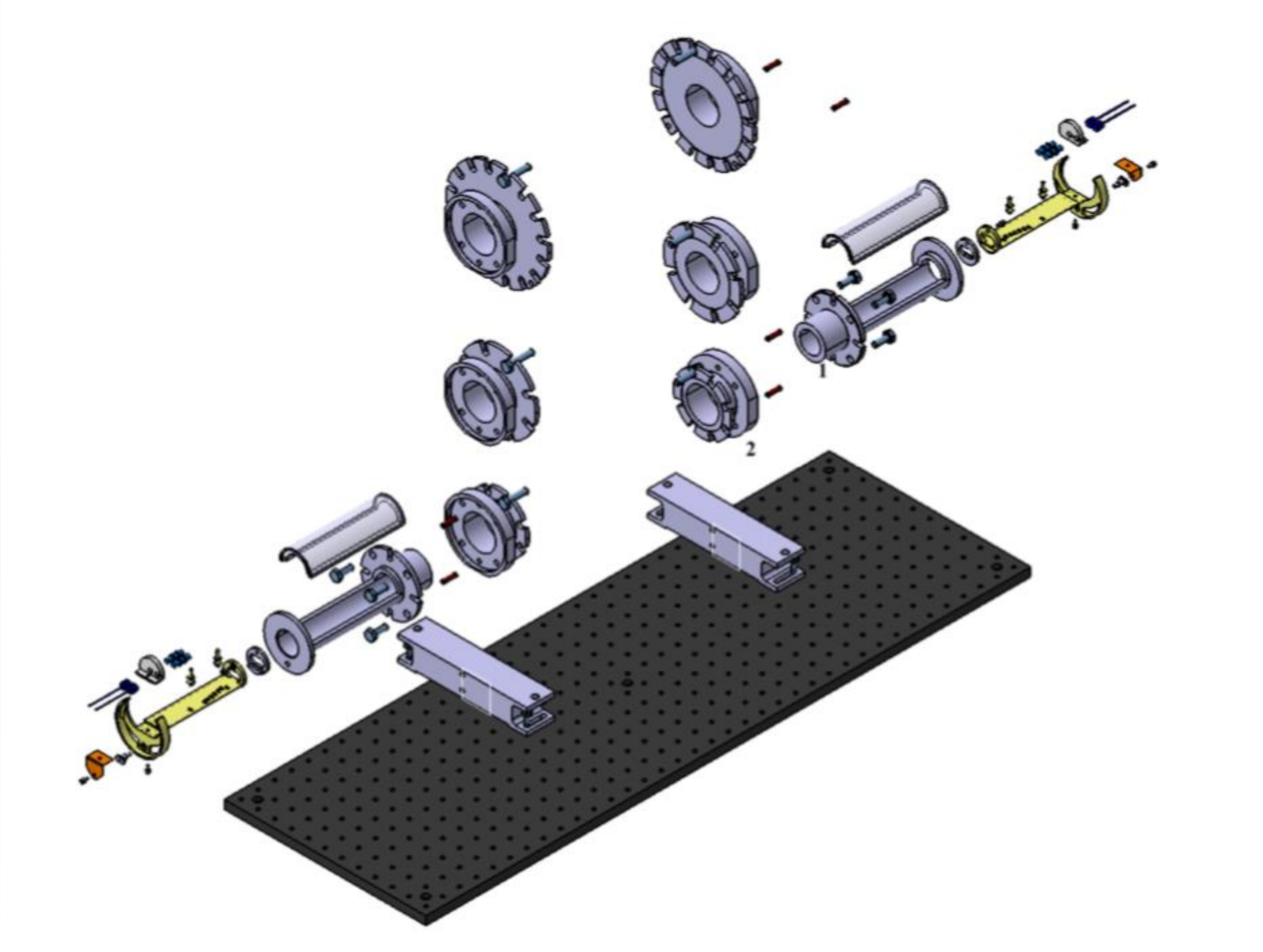
$$Z = -2Z_L \ln\left(\frac{S21_{DUT}}{S21_{REF}}\right)$$

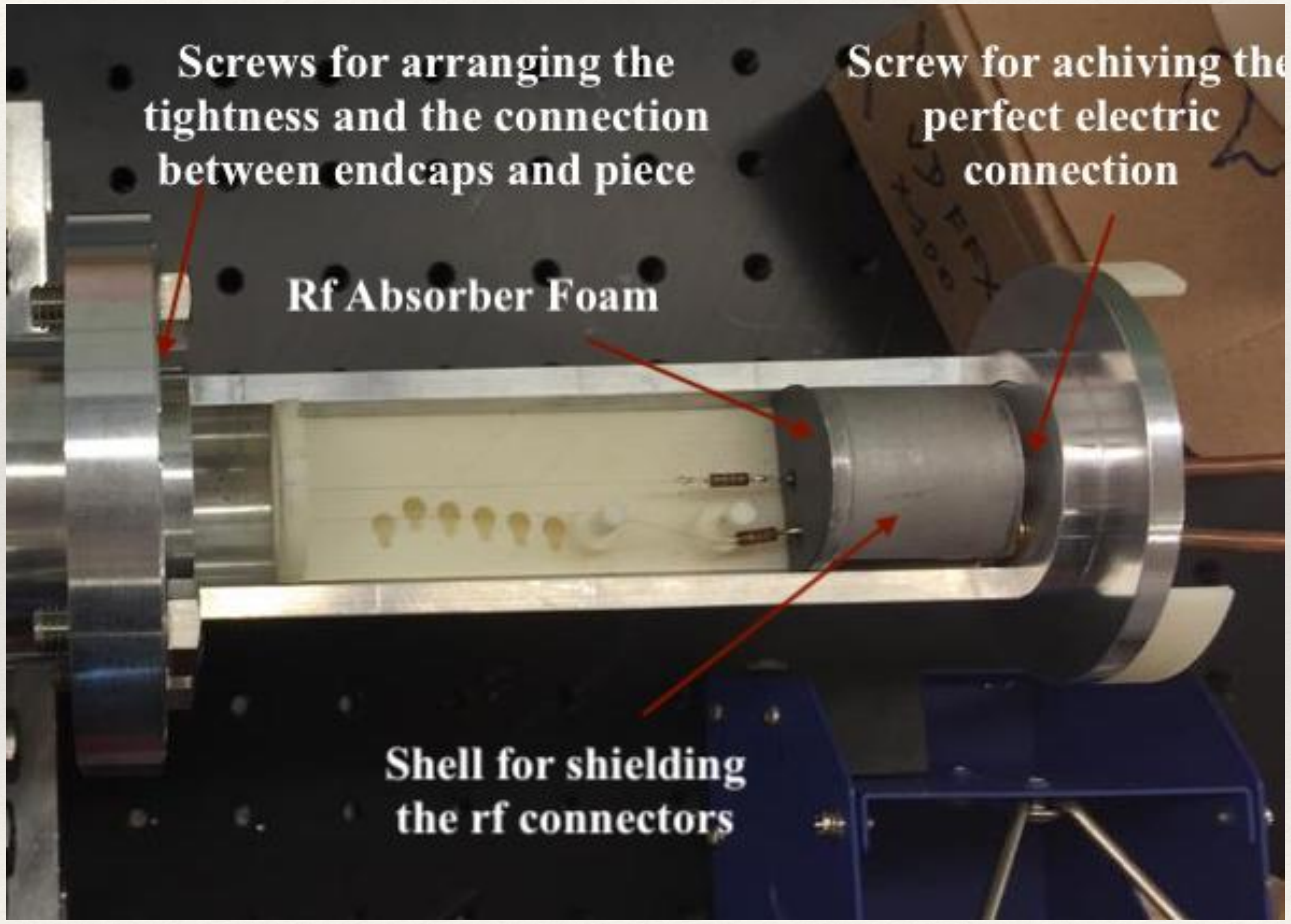
$$Z_L = \frac{Z_v}{2\pi} \ln\left(\frac{D}{d}\right)$$



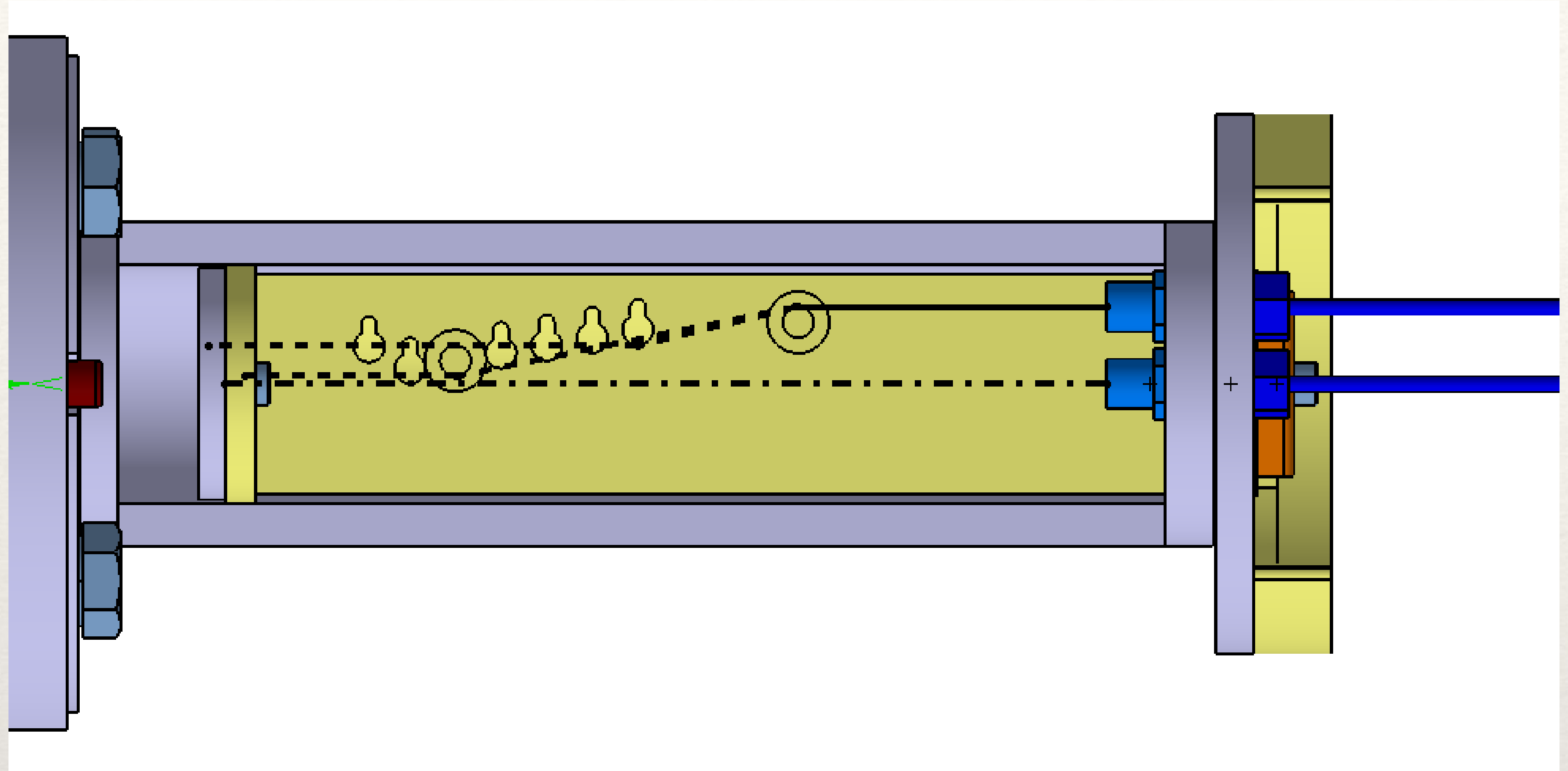
where Z_L is the line impedance $S21_{DUT}$ is the measured S parameter of the device under test and $S21_{REF}$ is the measured S parameter of the referance section,D is the diameter of the pipe($D_{eq} = 30.9mm$ was used) and d is the diameter of the wire.

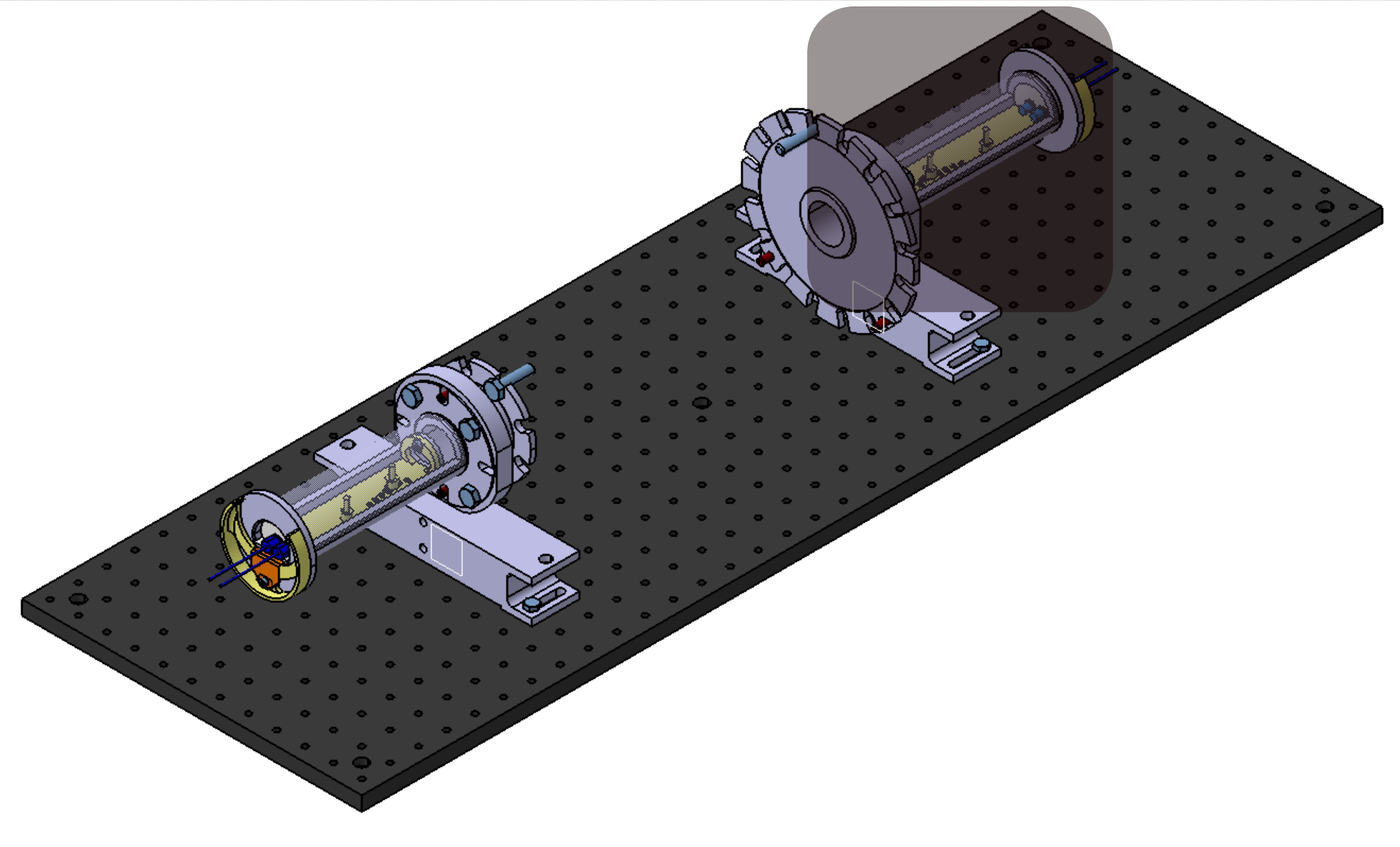
Design and Reliability of the Bench

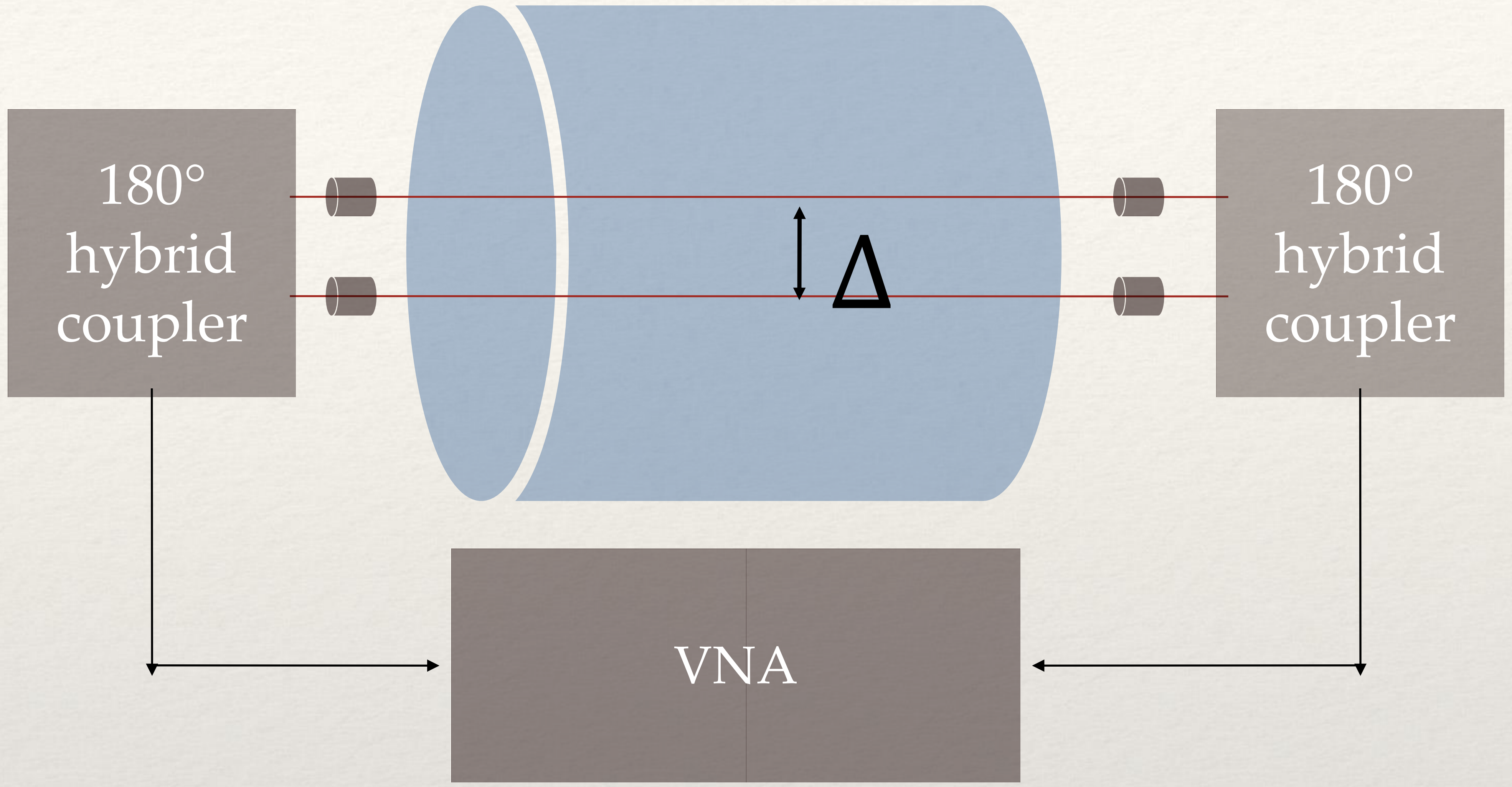




Two wire Measurements





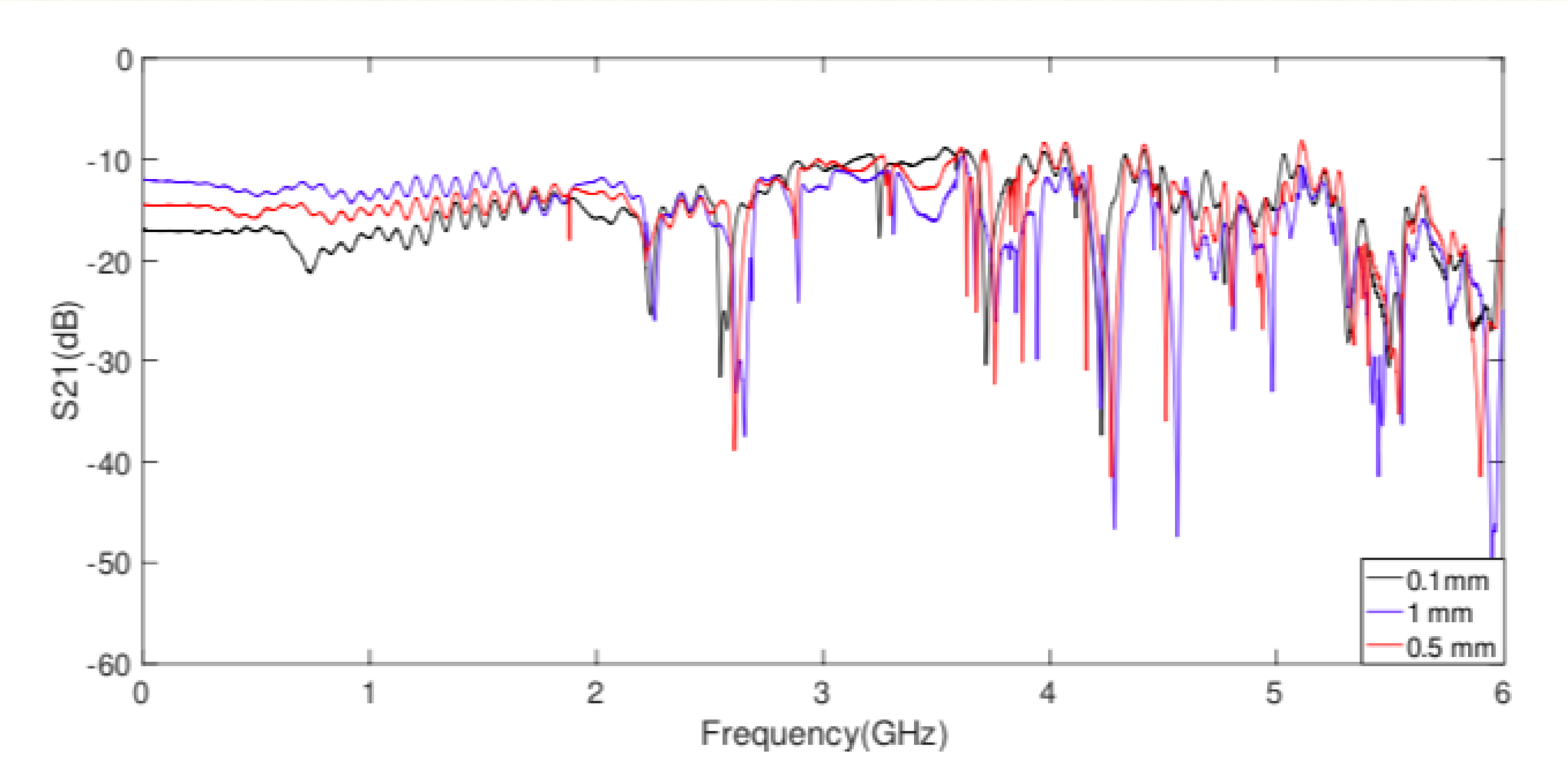


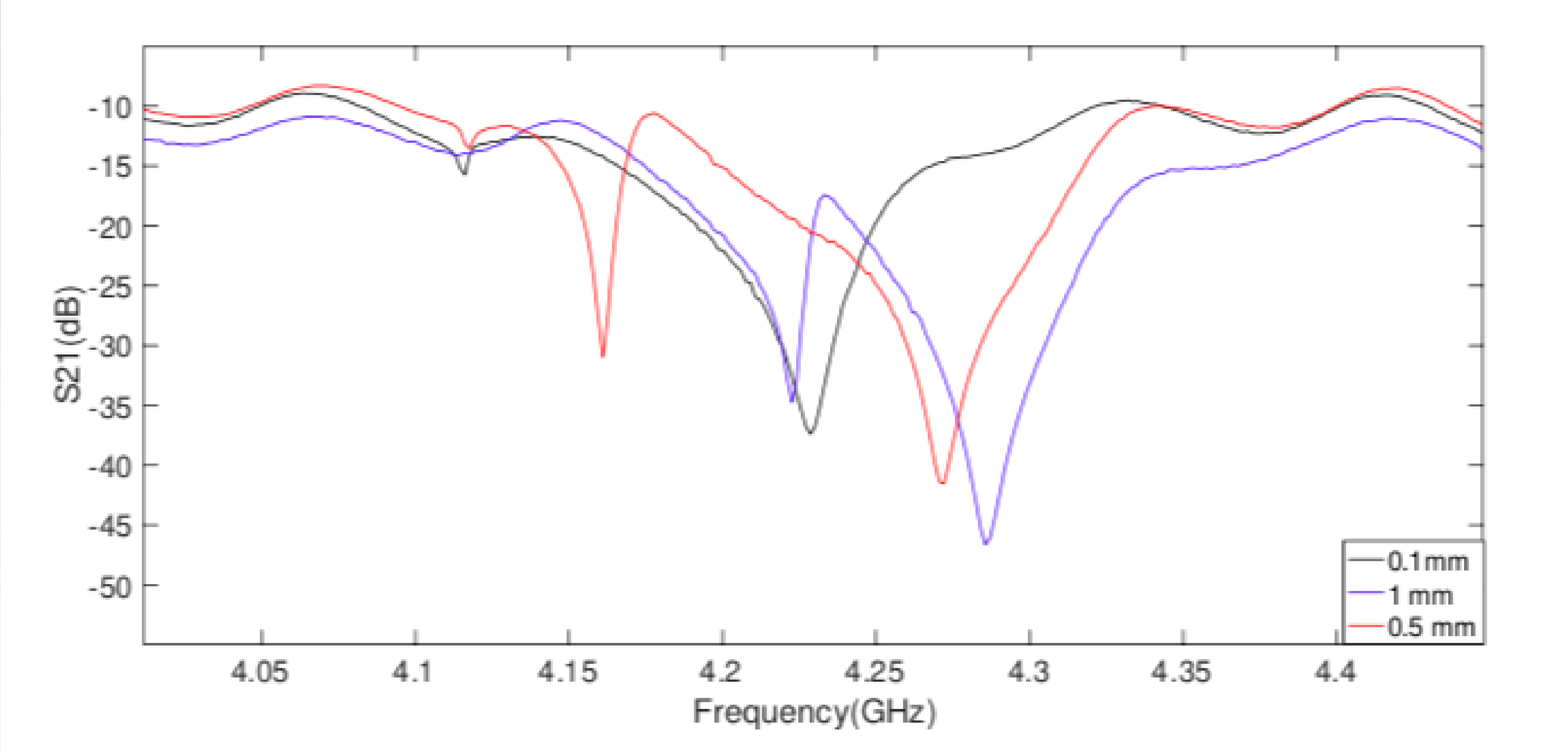
- Two wire method contains two wires driven with opposite phases which only gives the dipolar contribution of the impedance
- $Z_T = \frac{cZ}{2\pi f \Delta^2}$ where Δ is wire spacing.

where w is the frequency and Δ is the distance between two wire

Tests for Measurements

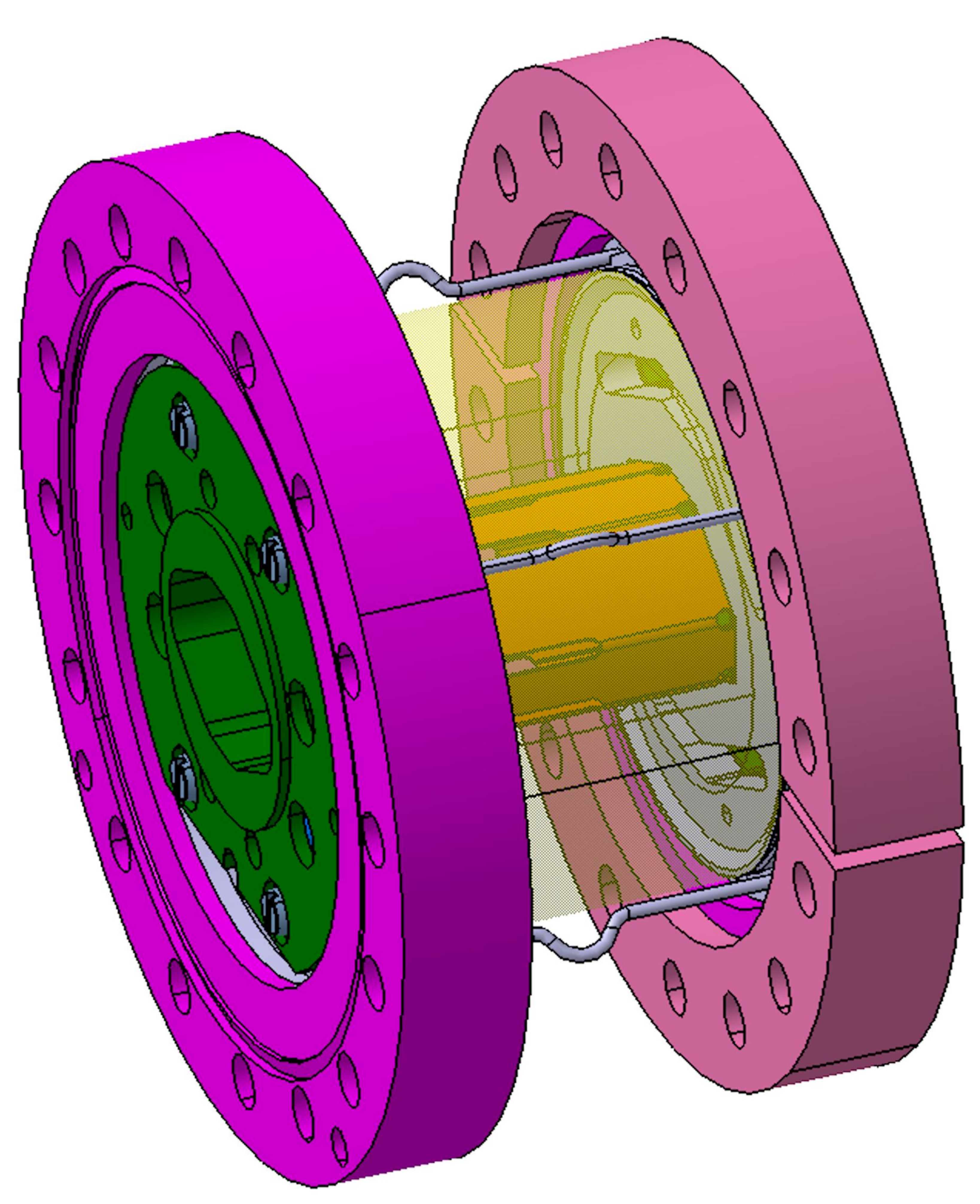
- Minimizing the parasitic and human error the measurements were performed 5 times.
- Different wire diameters were checked to find compromised between attenuation on the signal and high line impedance.



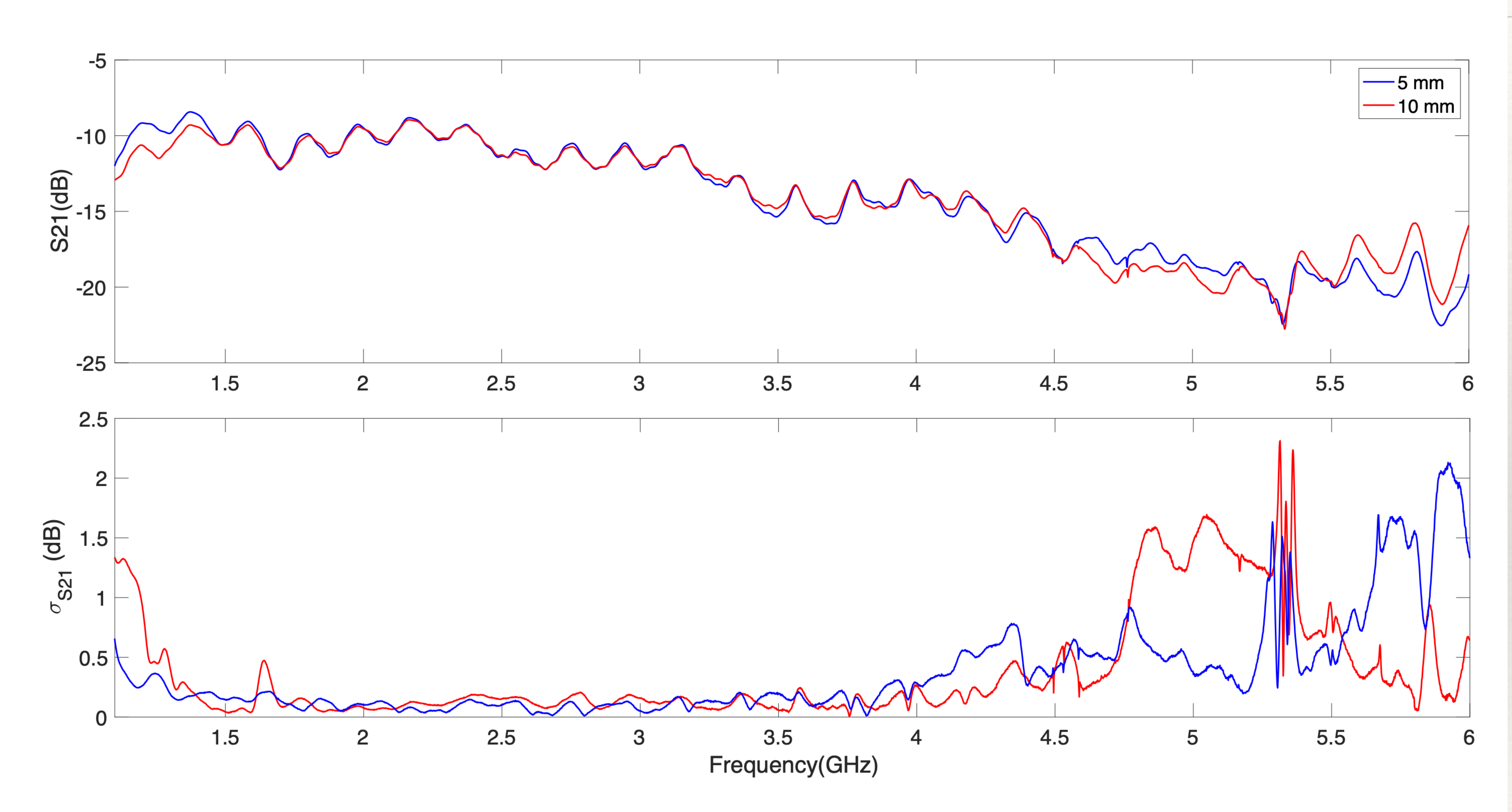


An Example for Two Wire: Bellow

- The Bellow aims to compansate termal expansions and contractions.
- They are also give sufficient tolerance for misalignments. Due to their geometry, bellows are tend to create high impedances and trigger higher order modes. These behavior can create beam instabilities and heats. The rf fingers can be used to shield rf fields to reduce impedances.
- The measurements can be performed without rf finger to check the reliability of the rf fingers but also reliability of the measurement bench.

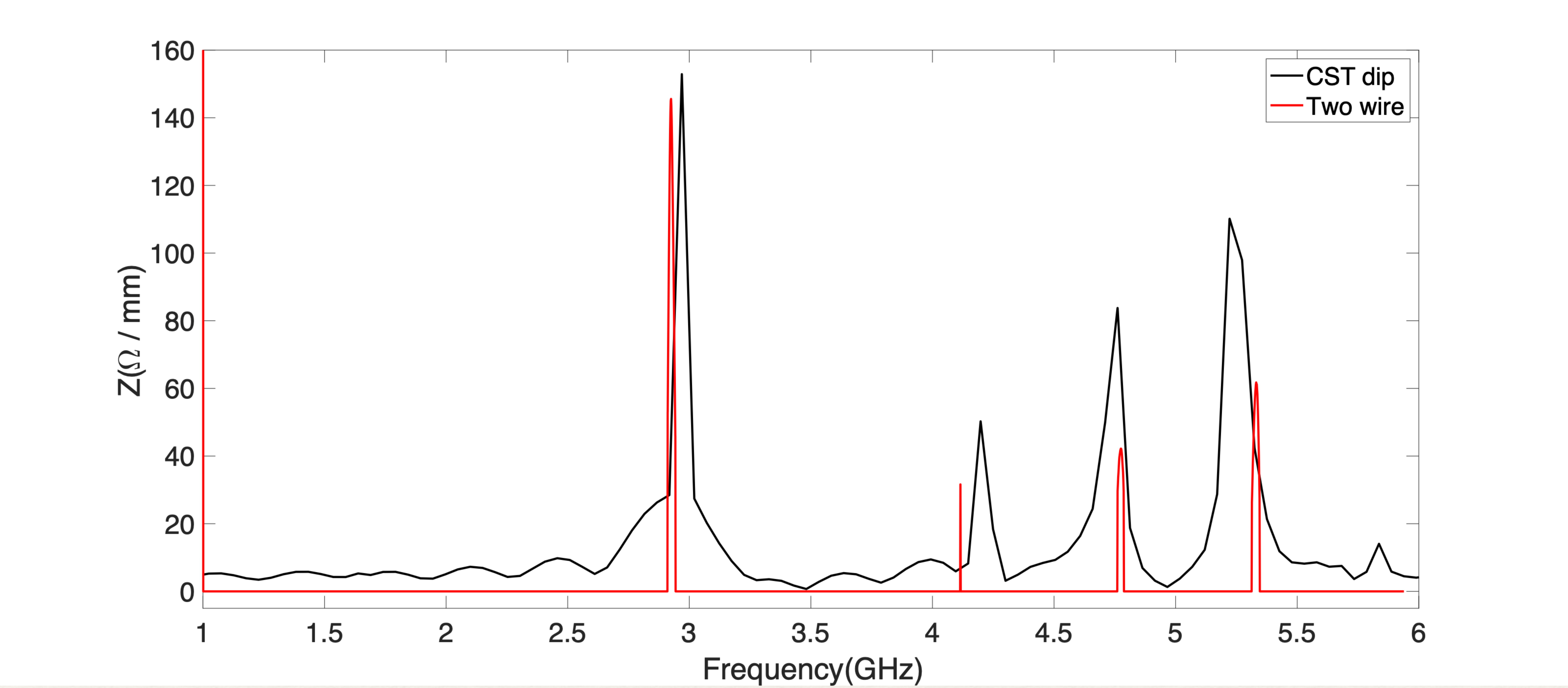


S Parameter Measurements of Reference



- The mean of 5 different S_{21} measurements with standard deviation

Dipolar Impedance Calculation and CST Simulation Comparison of Bellow

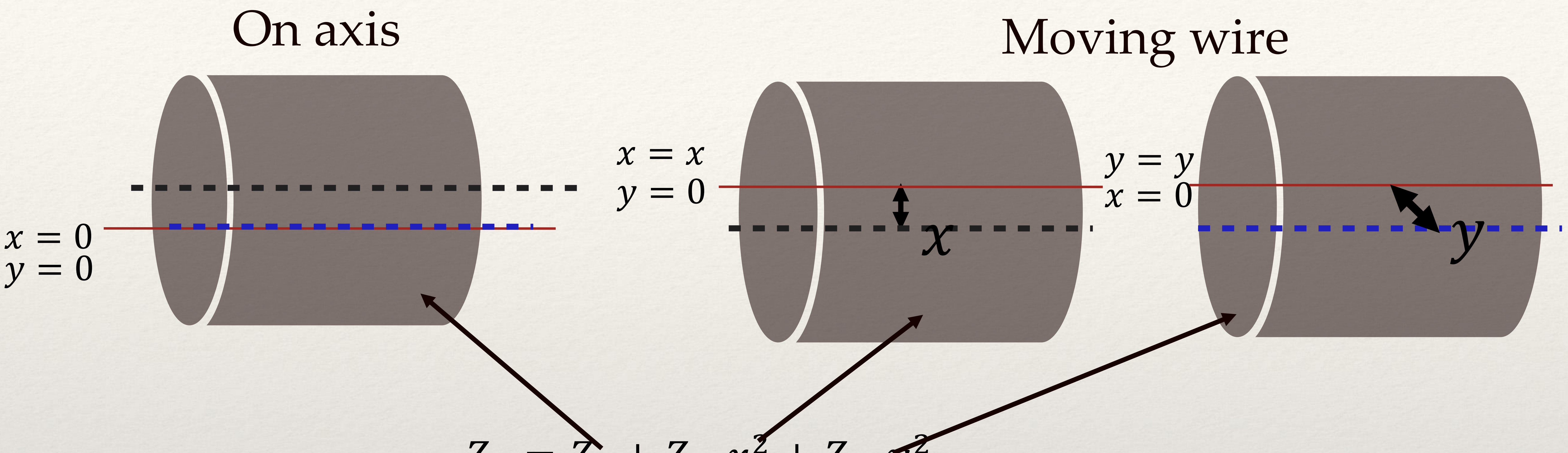


$$Z_T = \frac{cZ}{2\pi f \Delta^2}$$

Bellow Transverse Impedance(Dipolar) Comparison with CST Simulations
(1 cm distance)

$$Z = -2Z_L \ln(\frac{S21_{DUT}}{S21_{REF}})$$

One Wire Measurements



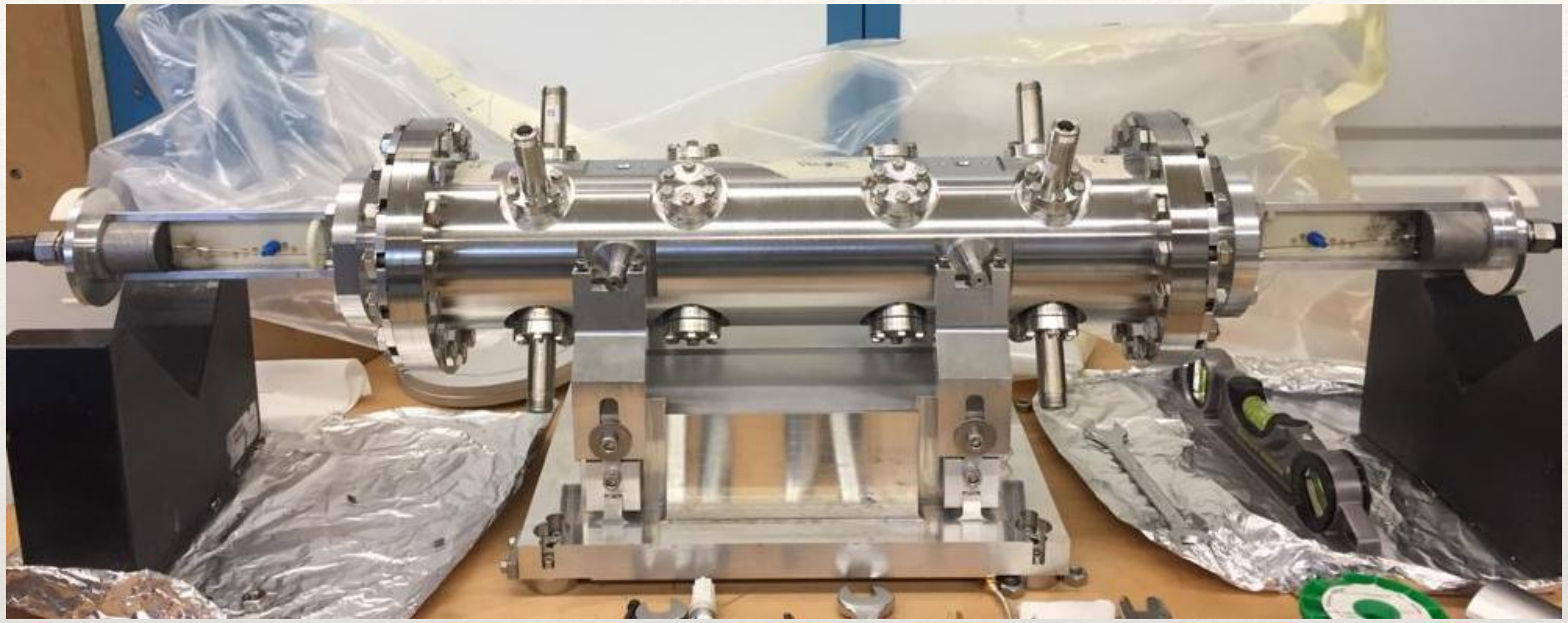
$$Z_T = Z_L + Z_{1x}x^2 + Z_{1y}y^2$$

- when it was measured at the center the only term you measured will be the Z_L which is the longitudinal impedance.

- where Z_L is the longitudinal impedance which was measured at the center, Z_{1x} and Z_{1y} are the measured impedance coefficents with and wire offset with x and y respectively.
- The general transverse impedances are:
- $Z_x = Z_{dipx} - Z_{quadx} = \frac{c}{2\pi f} Z_{1x}$
- $Z_y = Z_{dipy} + Z_{quady} = \frac{c}{2\pi f} Z_{1y}$
- The coefficient Z_{1x} and Z_{1y} are extracted by fitting a parabola.

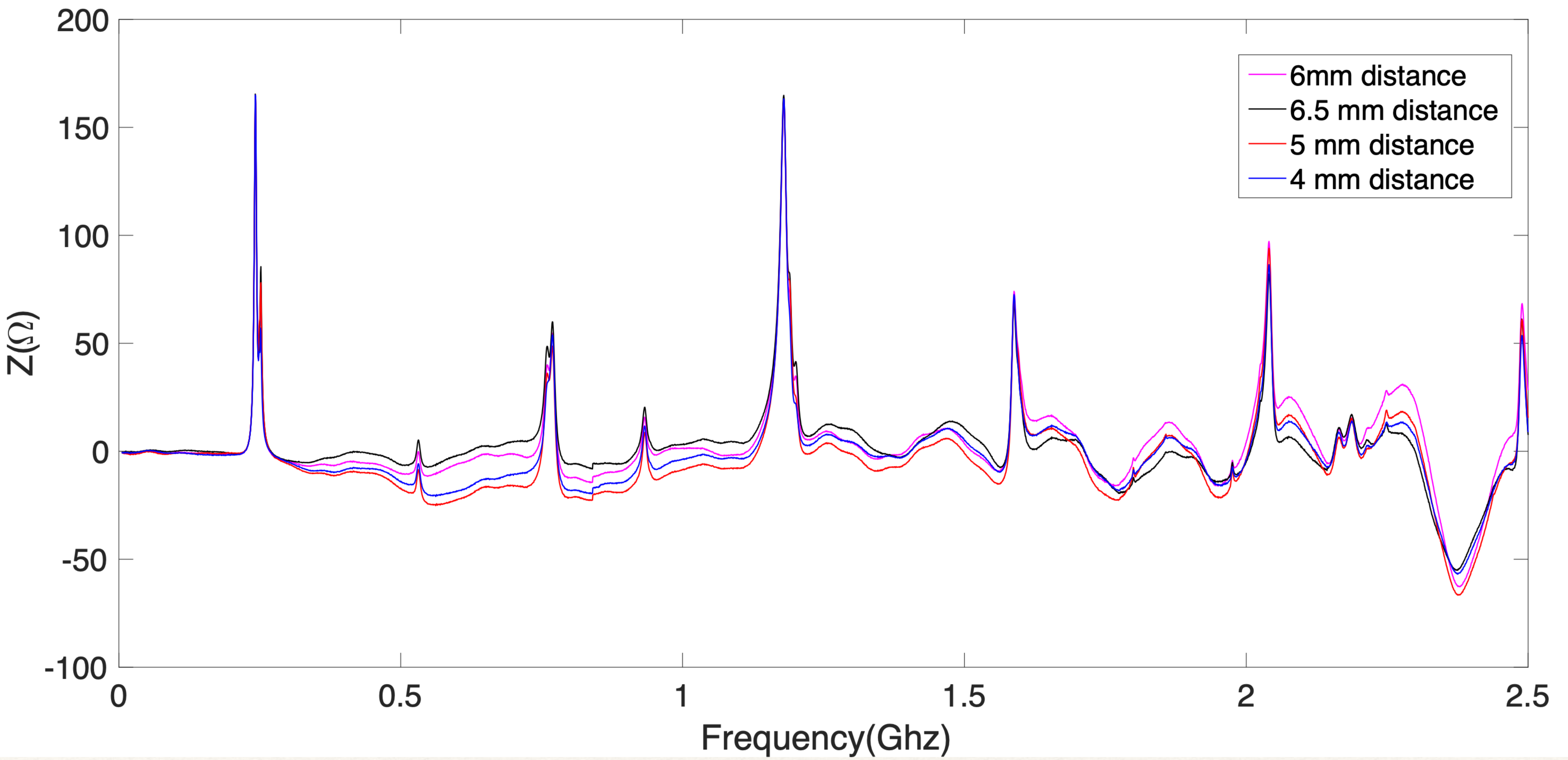
The moving wire measurements in both planes can be crosschecked with the two wire measurements.

An Example for Longitudinal and Moving Wire: FBT

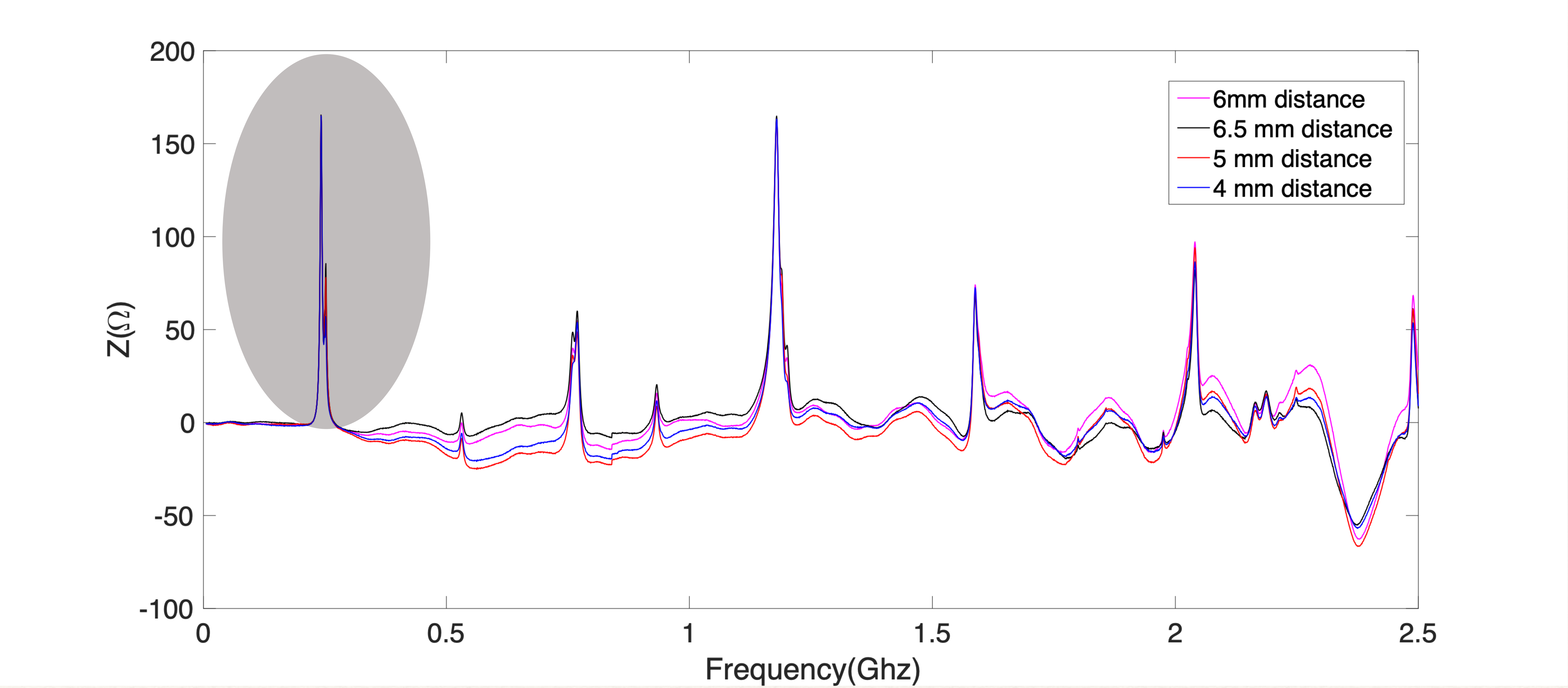


- The transverse feedback kicker is a part of the system which is aim to suppress beam instabilities with a fast response. The system is capable of detecting a coherent transverse motion(with BPM) and applying a counter kick to damp it (FBT), bunch by bunch and turn by turn.

Moving wire Measurements of FBT



Moving wire Measurements of FBT



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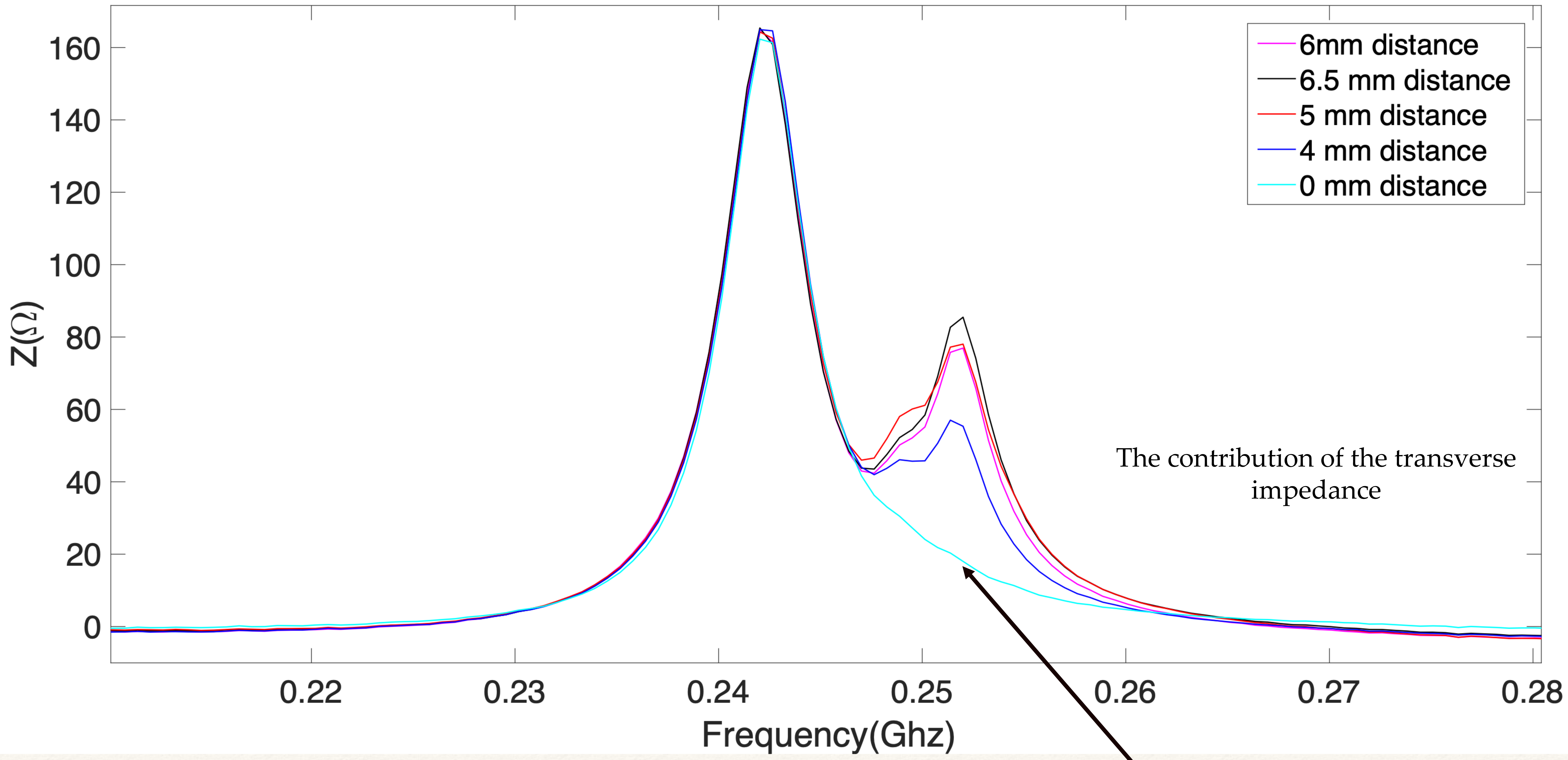
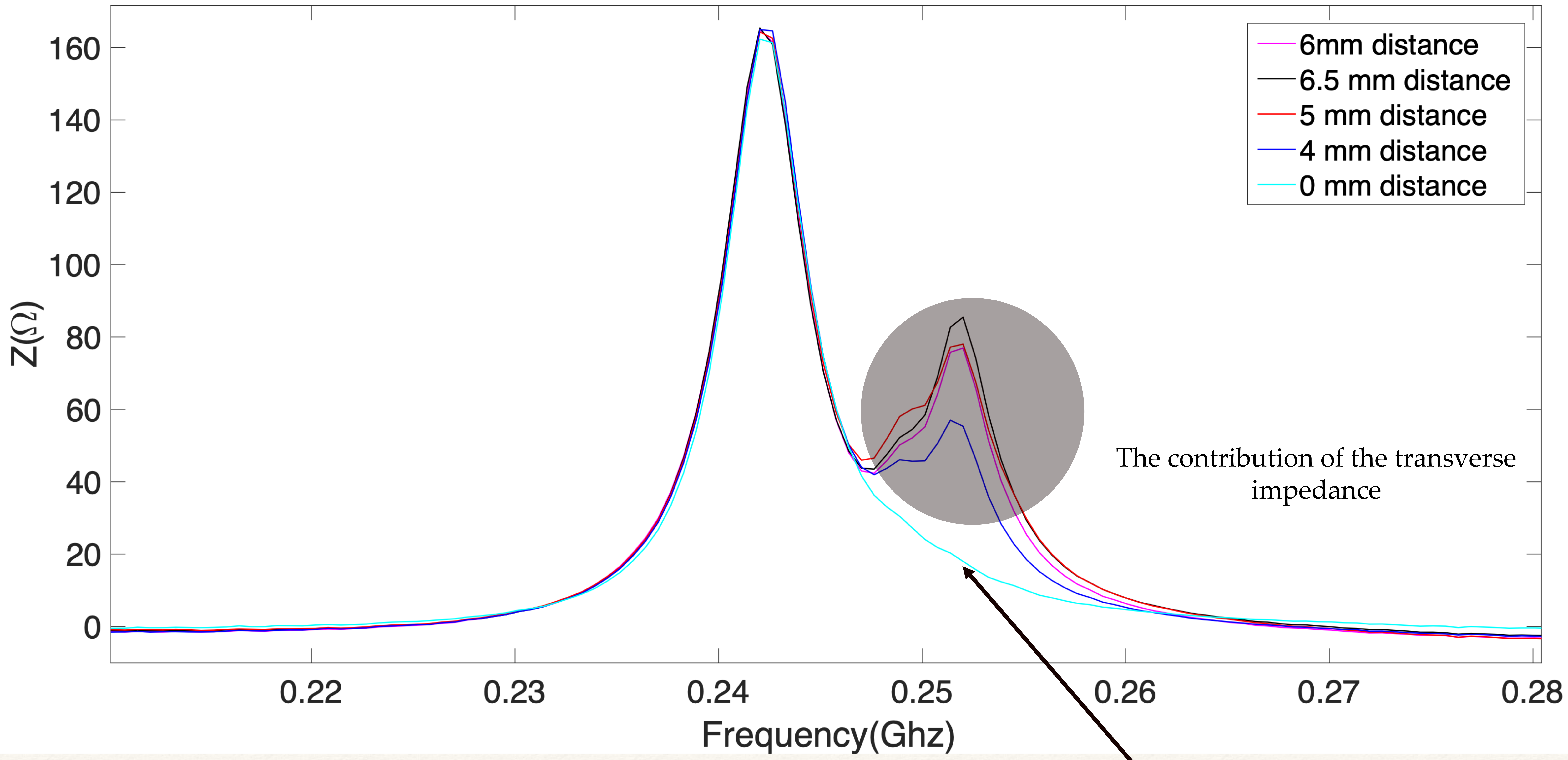


The fair blue one is on axis measurements which is longitudinal impedance of FBT.

Moving wire Measurements of FBT



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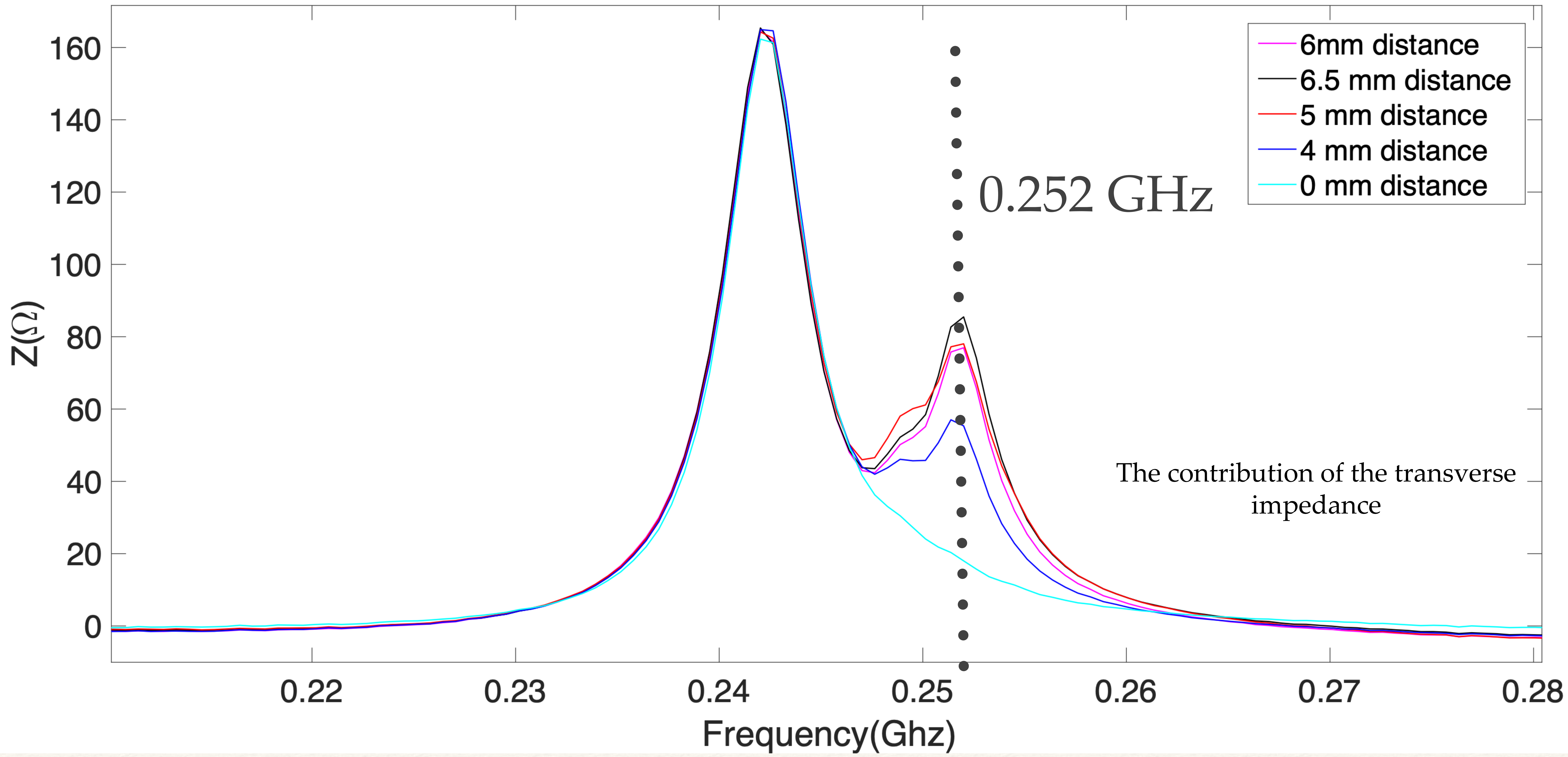
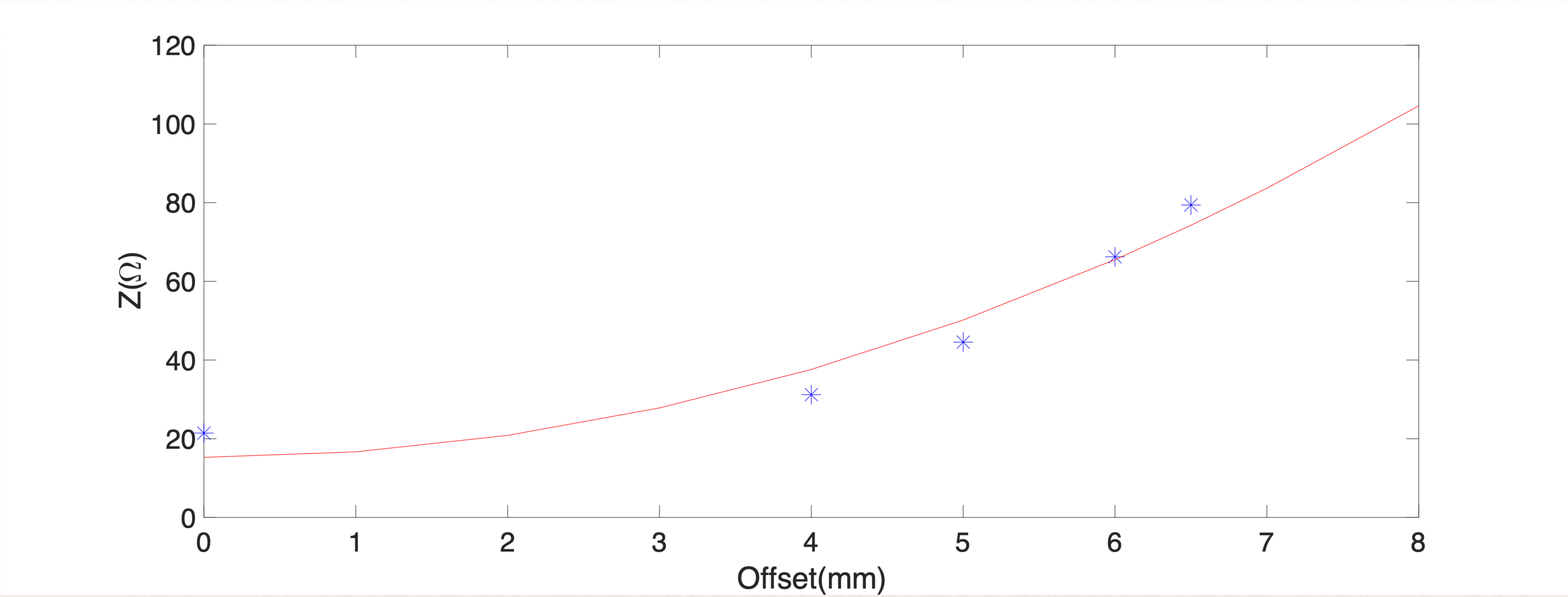
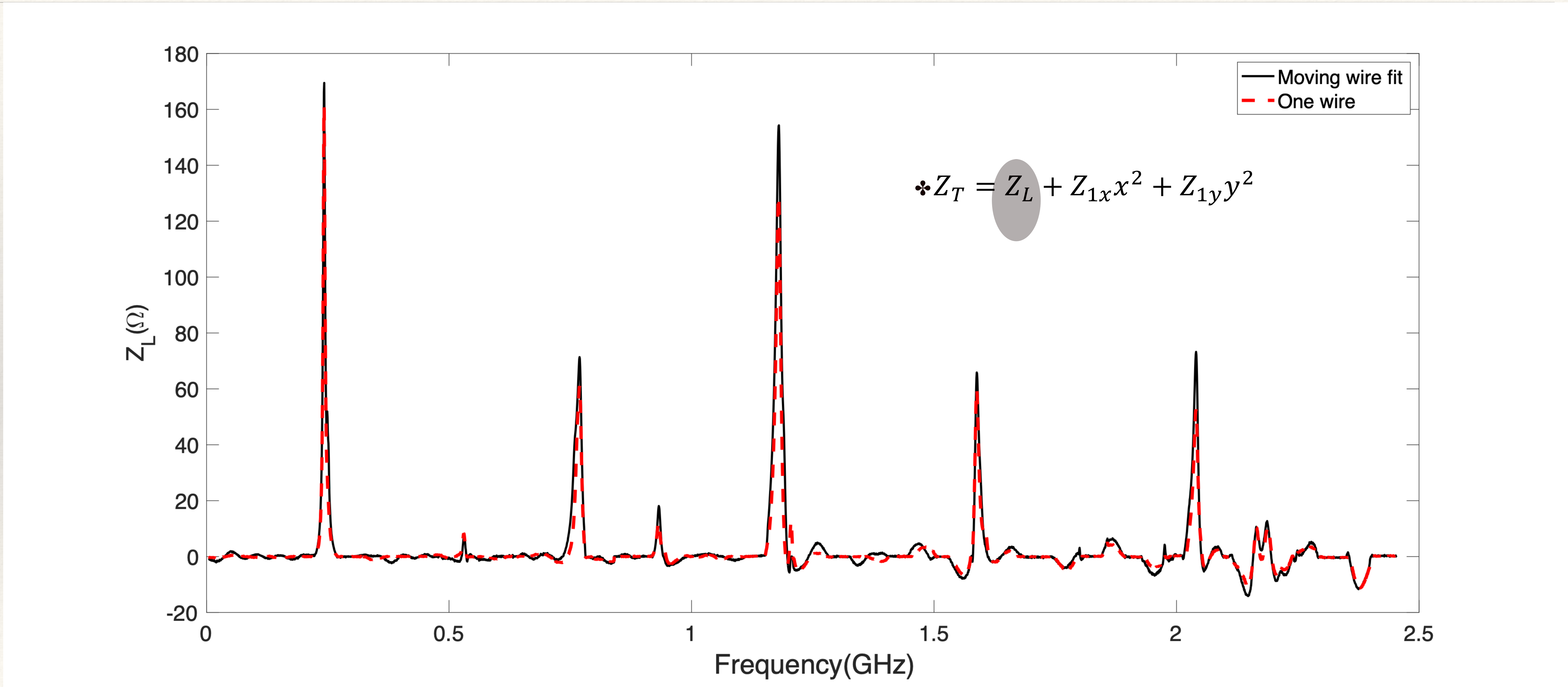


Parabolic fit Example



$$Z_T = Z_L + Z_{1x}x^2 + Z_{1y}y^2$$

Longitudinal Impedance Results



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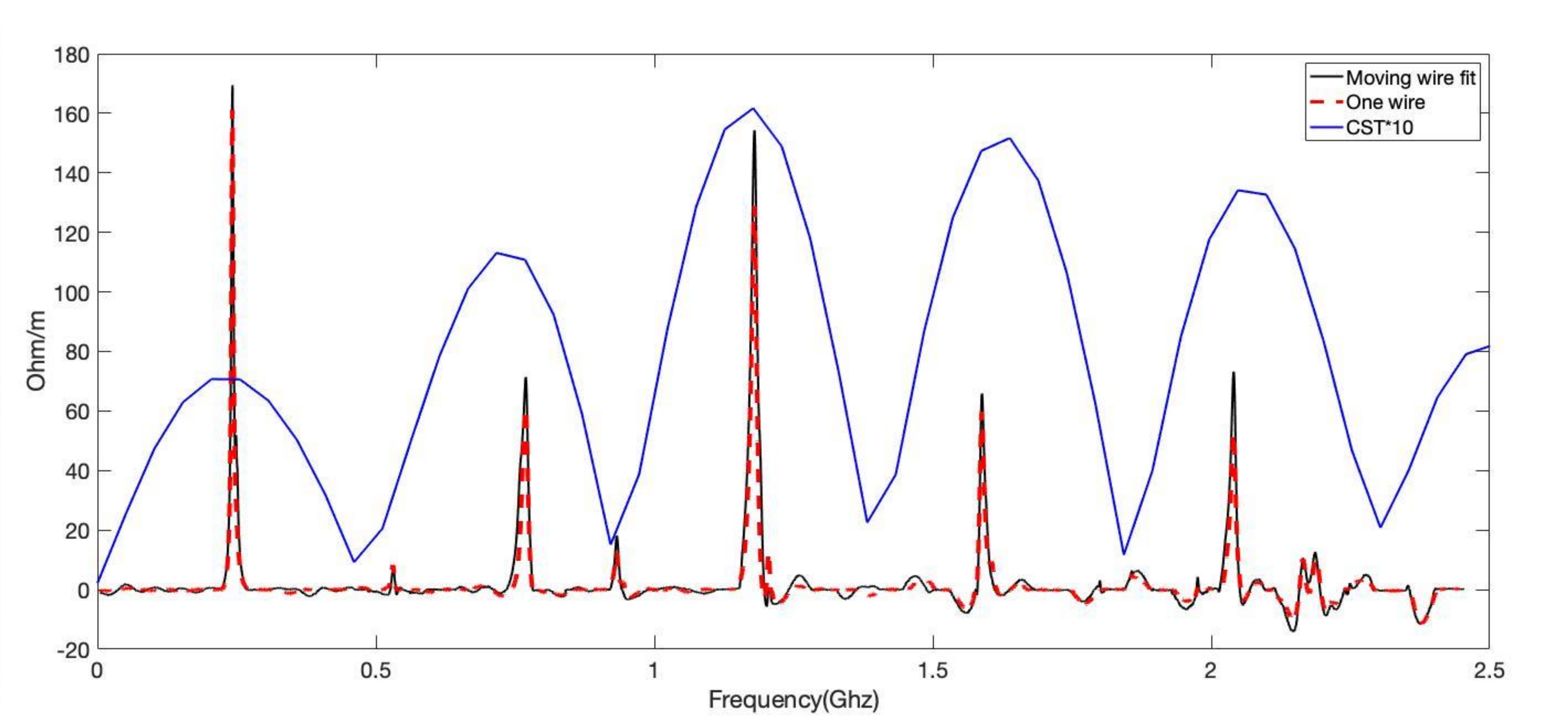
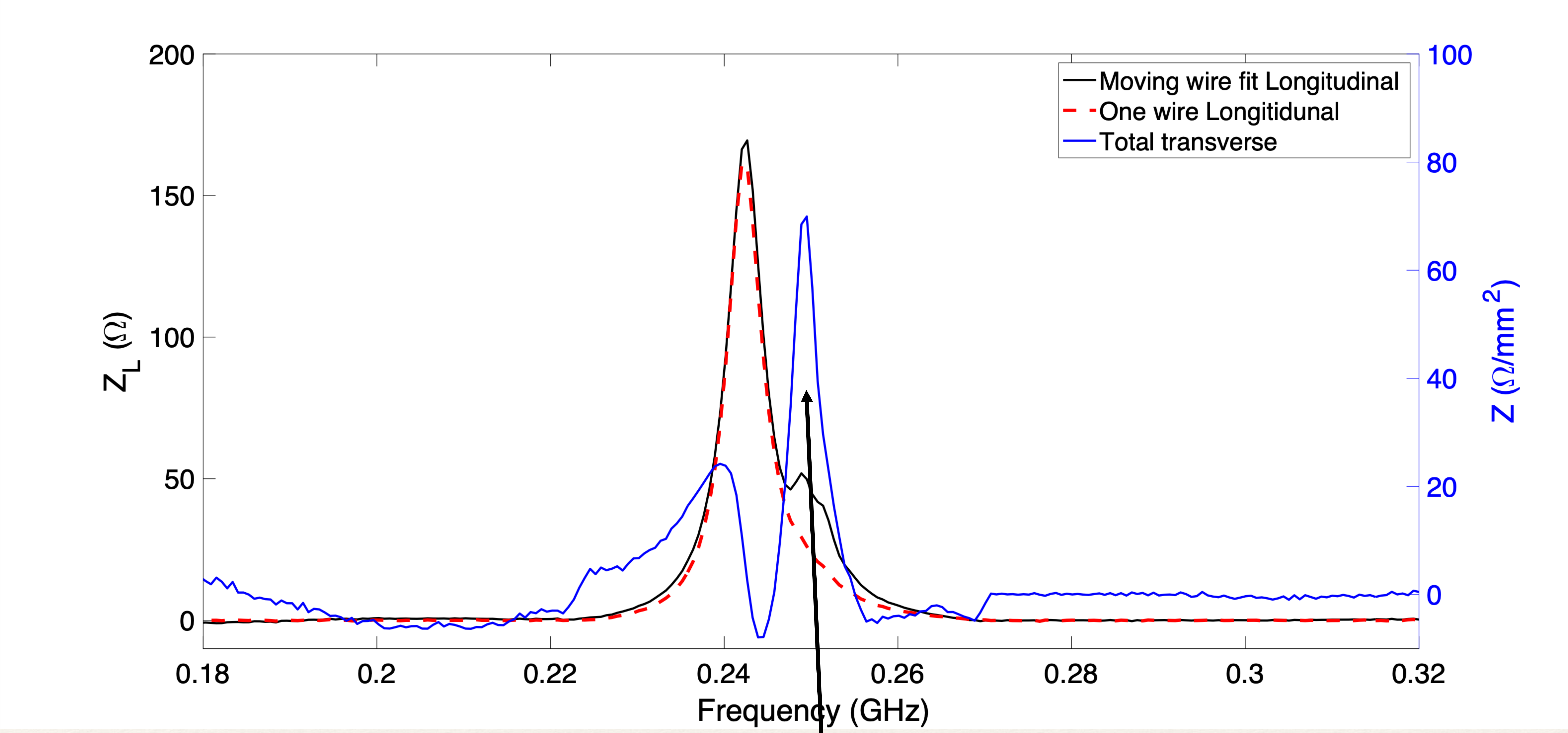
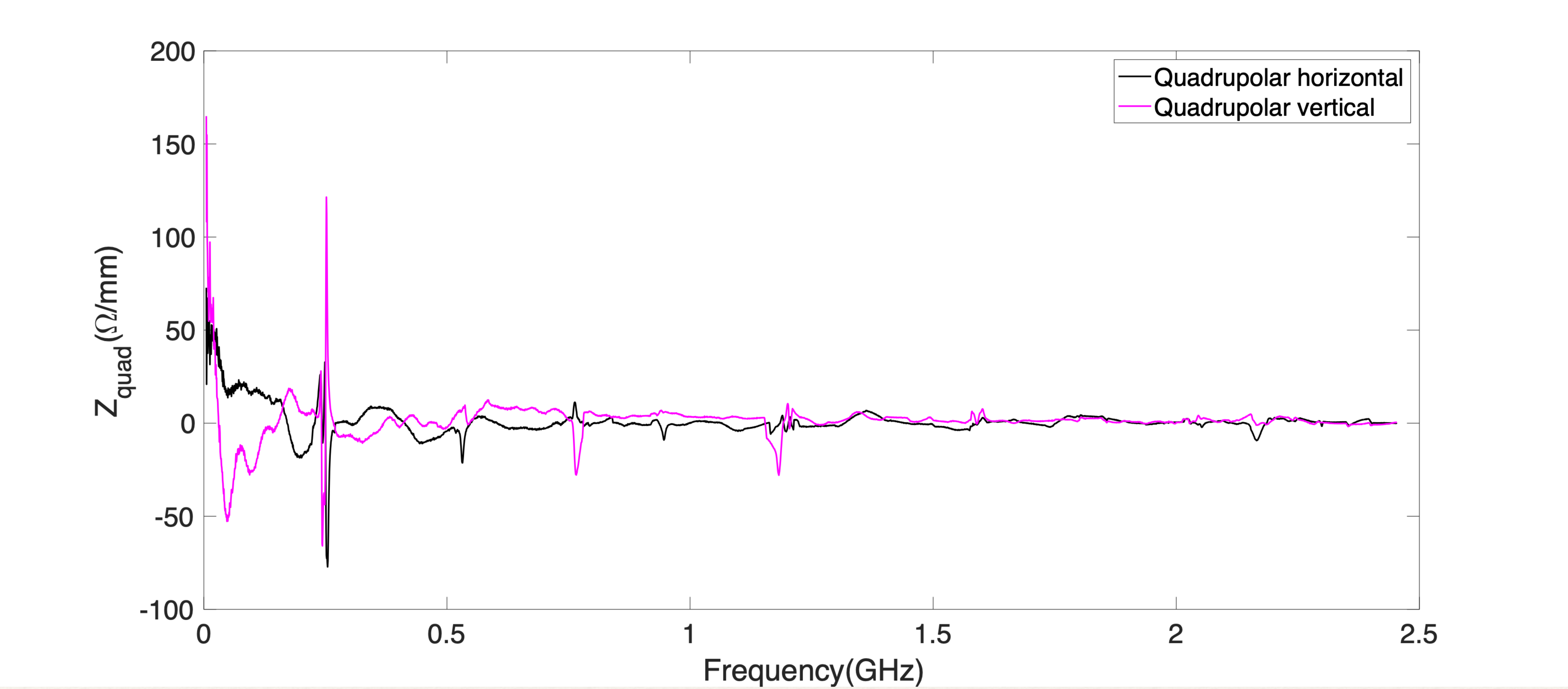


Total Transverse of FBT



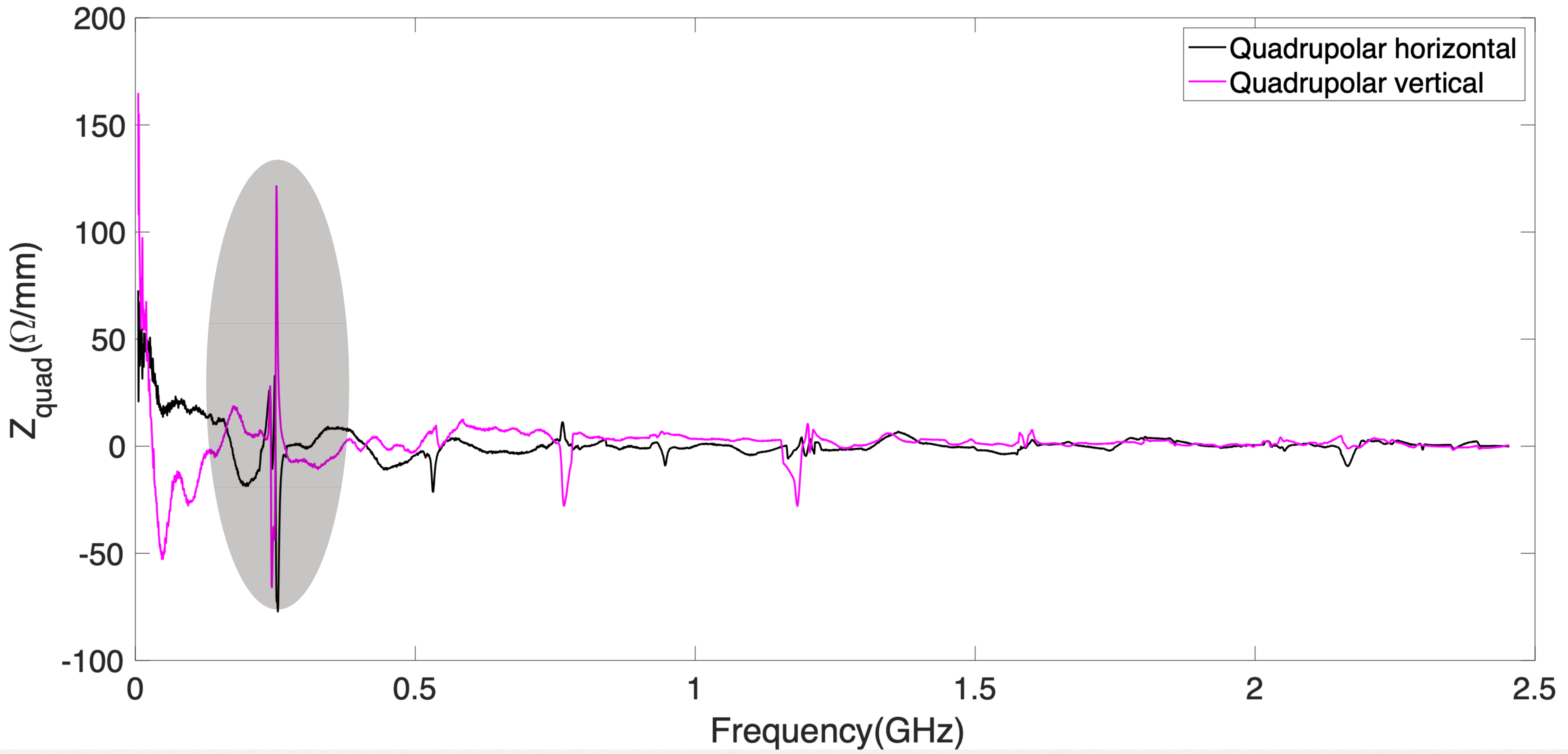
$$Z_T = Z_L + Z_{1x}x^2$$

Quadrupolar Impedance



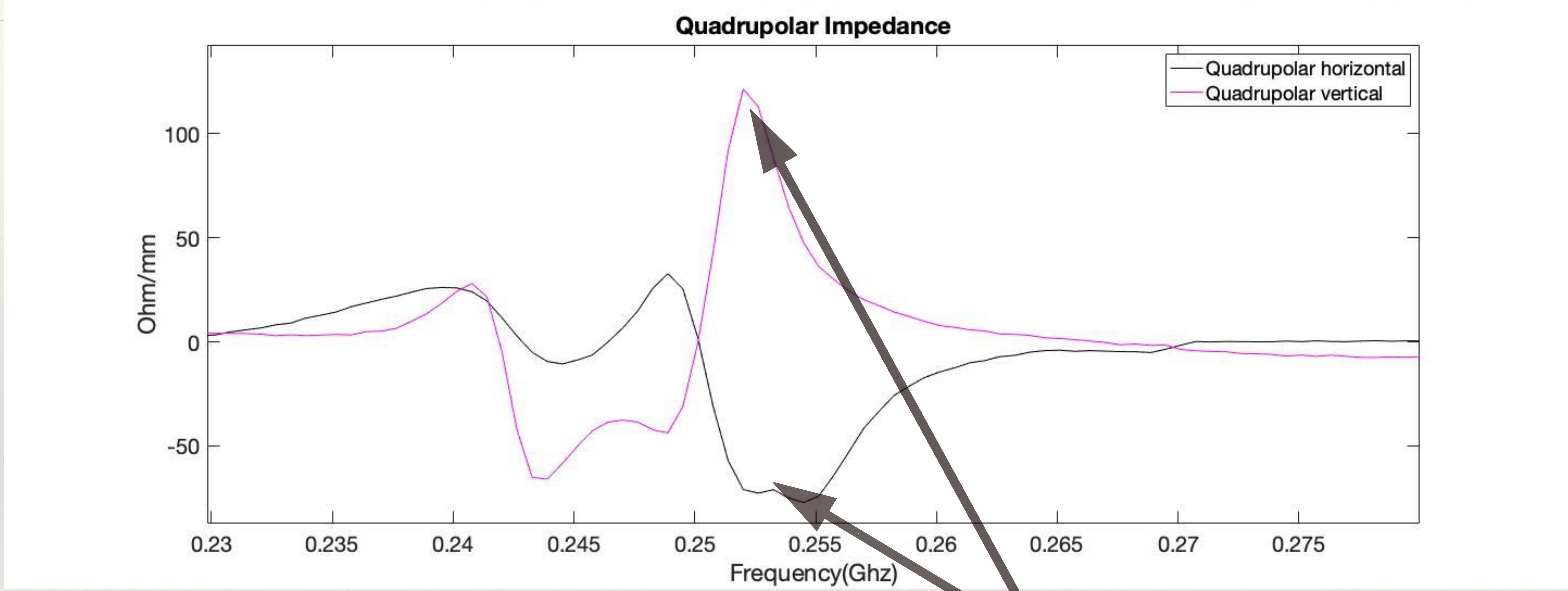
- The quadrupolar impedance which was taken as dipolar impedance extracted from total transverse impedance

Quadrupolar Impedance



- The quadrupolar impedance which was taken as dipolar impedance extracted from total transverse impedance

Quadrupolar Impedance

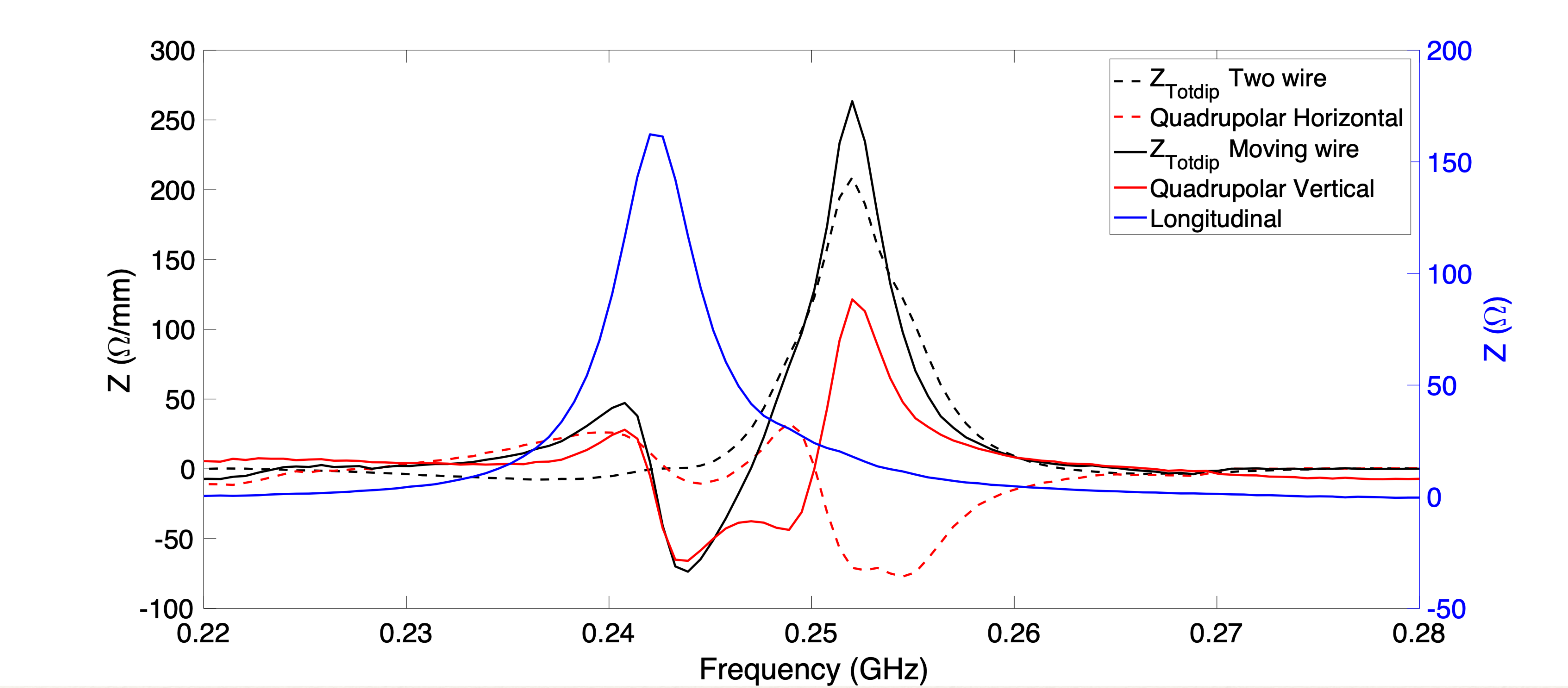


- The quadrupolar impedance which was taken as dipolar impedance extracted from total transverse impedance

$$Z_x = Z_{dipx} - Z_{quadx} = \frac{c}{2\pi f} Z_{1x}$$

$$Z_y = Z_{dipy} + Z_{quady} = \frac{c}{2\pi f} Z_{1y}$$

All impedances FBT



Conclusion

The total horizontal and vertical dipolar kick factors are −0.00088V/pC/m and −0.0011V/pC/m.

Total horizontal and vertical quadrupolar kick factors are 0.003976V/pC/m and 0.0033986V/pC/m respectively.

Maximum error is ~%5 in the frequency scale for all measurements from 0 to 6 GHz.

The longitudinal impedance can be measured from 9 Ω

The quadrupolar impedance can be extracted from moving wire even from 8 Ω/mm

Thank you for your Attention!

Back-ups

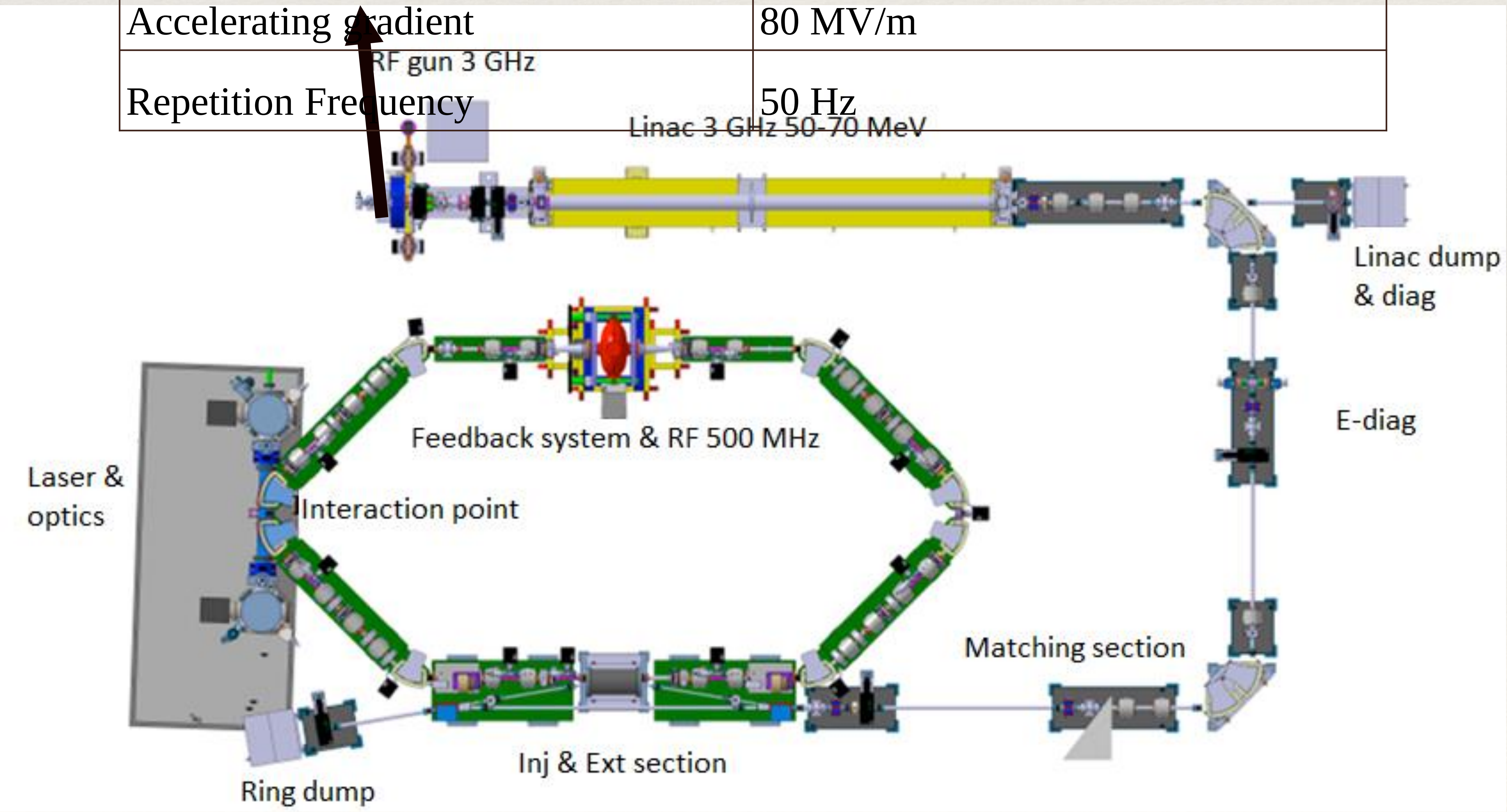
Relation Between Logaritmic and Linear

$$S(dB) = 20 * Log(\sqrt{reS^2 + imS^2})$$

$$Z_{log}(\Omega) = 20 * Log(\sqrt{reZ^2 + imZ^2})$$

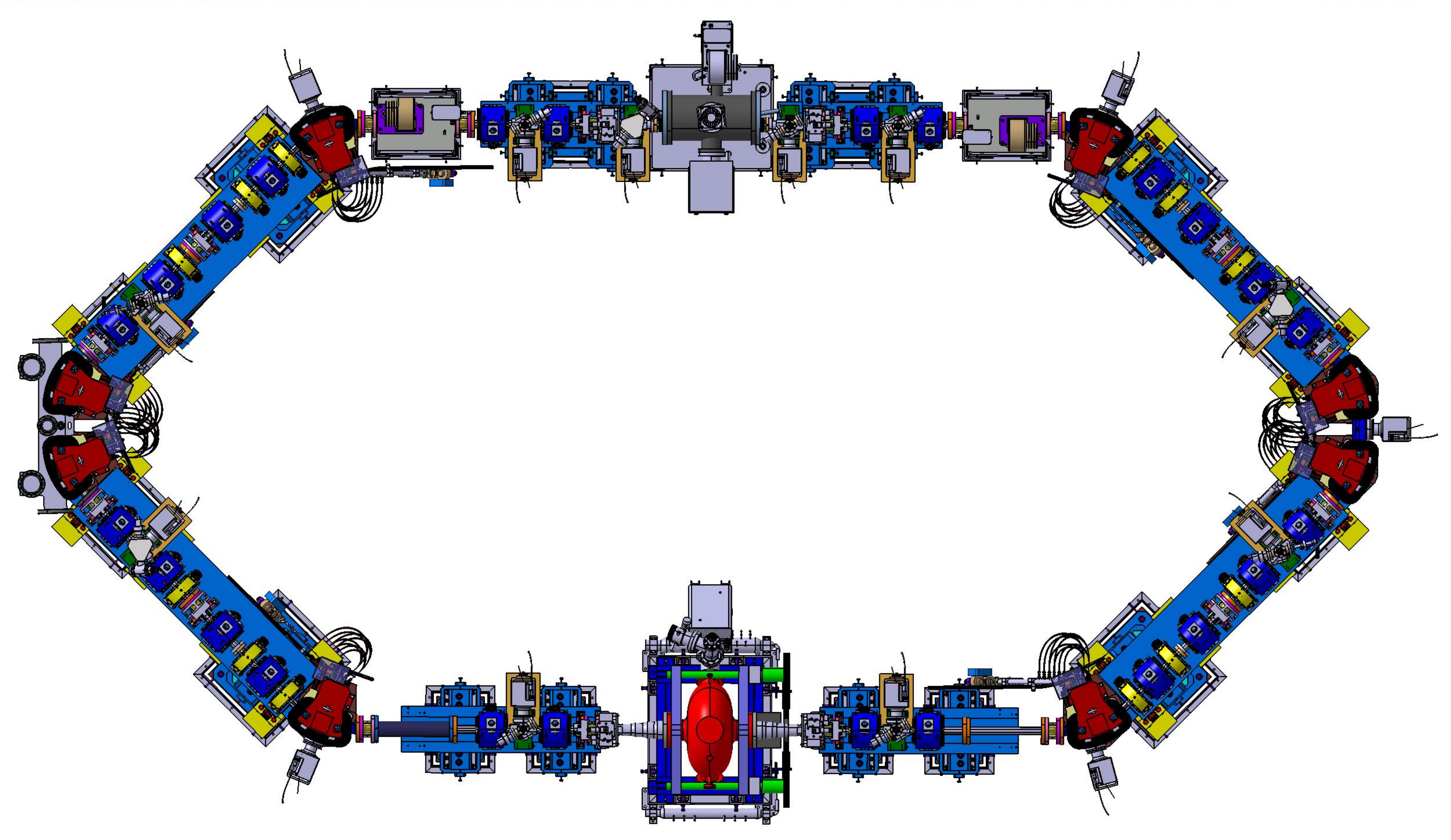
ThomX-Injection and Linac

Beam energy E at exit and charge	5 MeV 1 nC
RF Frequency	3 GHz
Number of bunches per RF pulse	1
Number of cells	2.5
Accelerating gradient	80 MV/m
Repetition Frequency	50 Hz



Beam energy E at exit	50 (70) MeV
Length	4.5 m
RF Frequency	3 GHz
Accelerating gradient	12.5 (18) MV/m
Electron bunch length $_s$ at the exit (@ 1 nC)	3-6 ps
Repetition Frequency	50 Hz
Emittance at exit (@ 1 nC)	5 pi.mm.mrad

ThomX Storage Ring



$$T_{store} = 20ms$$

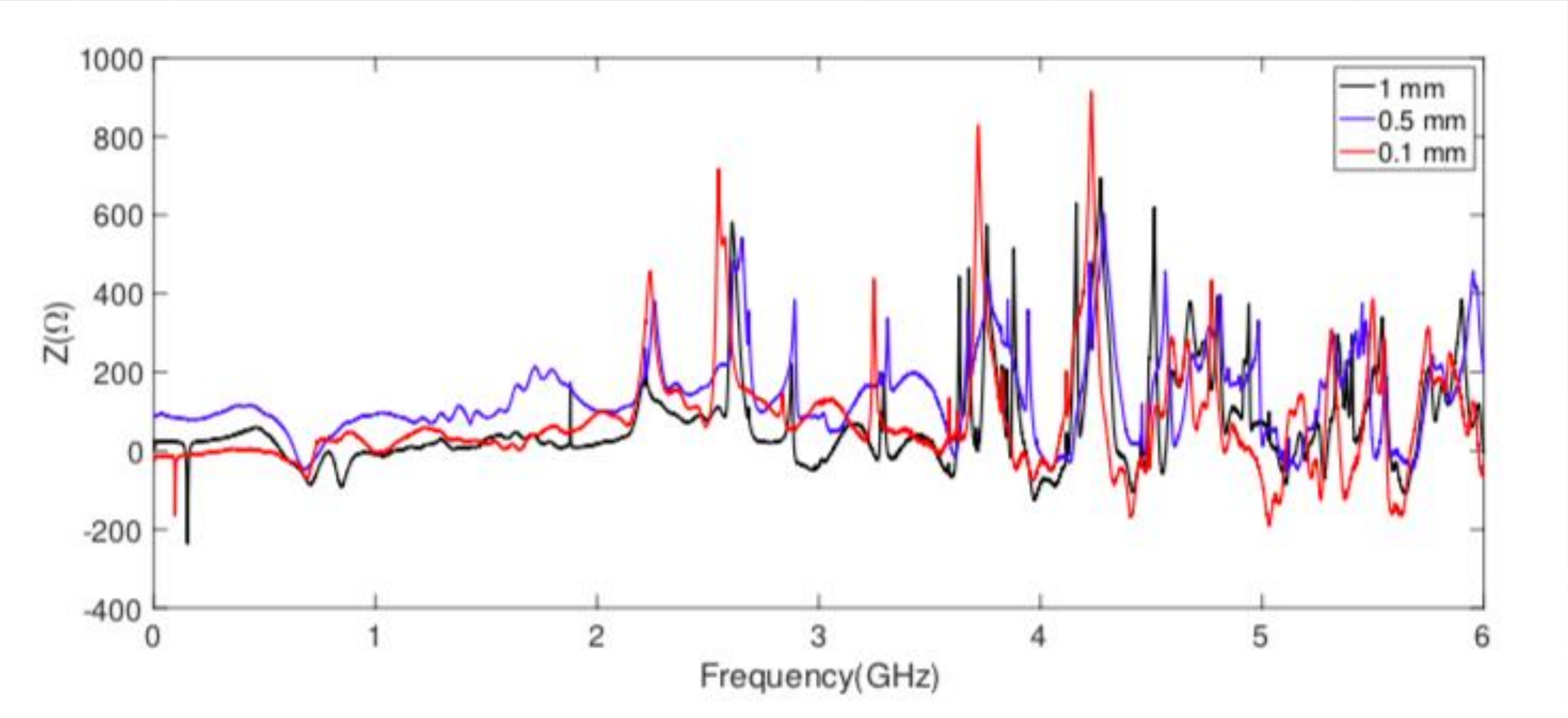
Beam energy E at exit	50 (70) MeV
Length	4.5 m
RF Frequency	3 GHz
Accelerating gradient	12.5 (18) MV/m
Electron bunch length $_s$ at the exit (@ 1 nC)	3-6 ps
Repetition Frequency	50 Hz
Emittance at exit (@ 1 nC)	5 pi.mm.mrad

Step in out Theory

$$h_l(z) = \frac{c}{\omega_l}(k_l(AJ_1(u) + BN_1(u))cos(k_l z) - \sqrt{(\omega_l/c)^2 - k_l^2}(CJ_0'(u) + DN_0'(u)))$$

Cst Simulations	Measurement results
0.46	–
1.43	–
2.35	2.24
2.45	2.54
3.11	3.25
3.63	3.72
4.19	4.23
4.76	4.76
5.37	–
5.99	–

$$\omega_l = c\sqrt{(x_{0l}/R)^2 + k_l^2} \qquad k_l = \frac{l\pi}{g}$$



Analytically calculated frequency	Cst Simulations	Measurement results
2.51	2.45	2.54
5.71	5.99	5.9
8.92	9.2	–

Error Estimation

$$Z(x,f) = Z_{Long} + Z_{1x}x^2$$

With another notation, it can be writtten as:

$$X = \begin{pmatrix} 1 \\ x^2 \end{pmatrix}$$

and

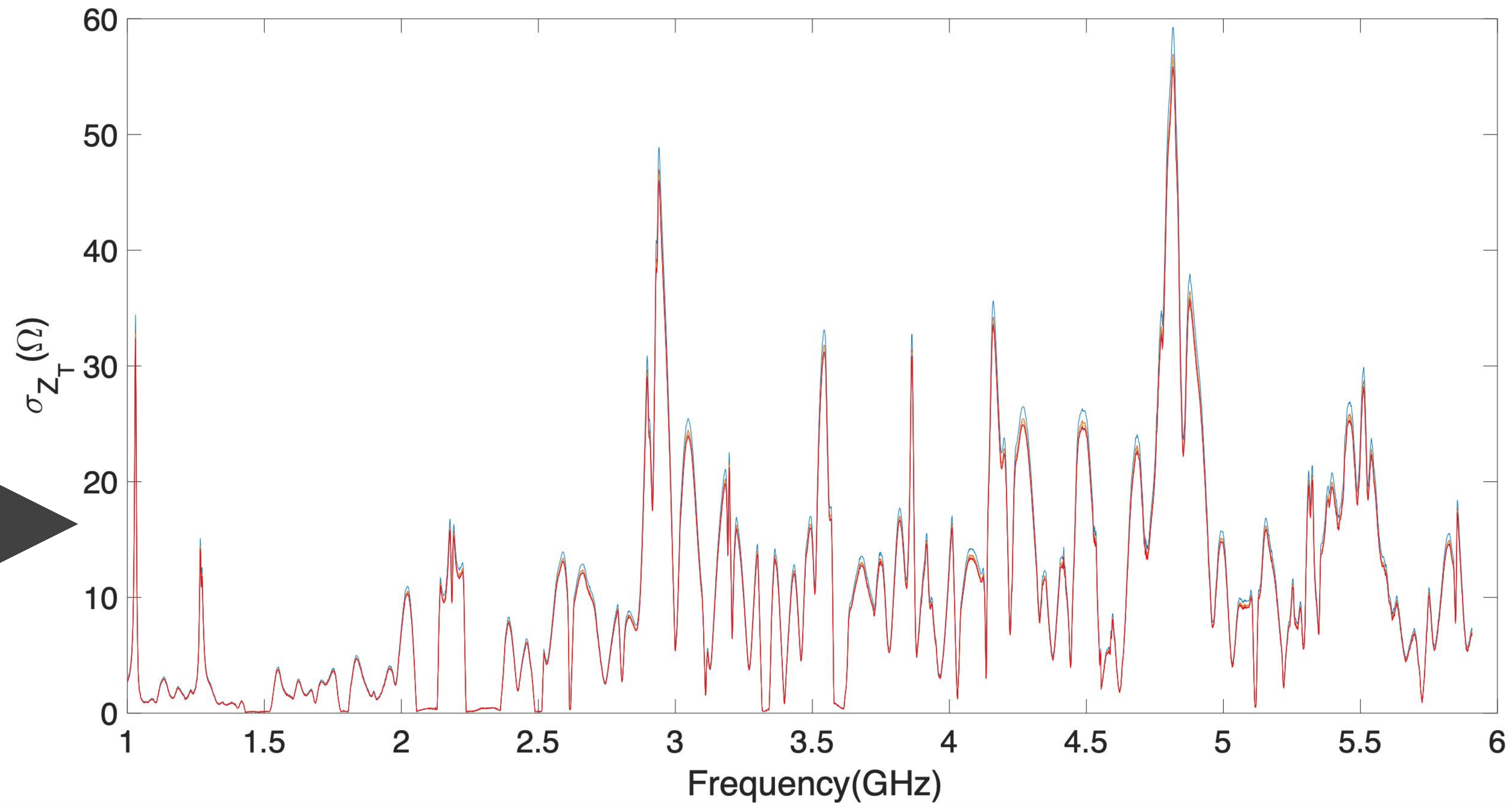
$$Y(x,f) = Z = \left(-2Z_L \ln(\frac{S21_{DUT}}{S21_{REF}}) \right)$$

and

$$\beta(f) = \begin{pmatrix} Z_{Long} \\ Z_{1x} \end{pmatrix}$$

$$Y(f) = X(x)^T \beta(f)$$

$$\sigma_Z = 2Z_L \sqrt{\frac{{\sigma_{S21_{DUT}}}^2}{{S21_{DUT}}^2} + \frac{{\sigma_{S21_{Ref}}}^2}{{S21_{Ref}}^2}}$$



Theory of Moving wire

The impedance can be defined with current density:

$$Z_{m,n} = \frac{-1}{I^2} \int dV\, \vec{E_m} . \vec{J_n} \qquad m, n = 0, \pm 1, \pm 2, \ldots$$

where Zm,n (m,n=0,±1,±2,...) are the impedances due to the n-th order current density, a is the displacement of the wire from the centre axis and θ is the azimuthal angle of displacement of the wire.

$$\vec{J_n} = \frac{I}{2\pi a^{|m|+1}} \delta(r-a) e^{jn\theta} e^{j(wt-kz)} e_z$$

In that case, the longitudinal impedance created by a single wire displaced from the center by a and with an azimuthal angle θ is :

$$Z = Z_{0,0} + ae^{-j\theta}(Z_{1,0} + Z_{0,-1}) + ae^{j\theta}(Z_{0,1} + Z_{-1,0}) + a^2 e^{-2j\theta}(Z_{2,0} + Z_{1,-1} + Z_{0,-2}) + a^2(Z_{1,1} + Z_{-1,-1}) + a^2 e^{2j\theta}(Z_{0,2} + Z_{-1,1} + Z_{-2,0}) + O(a$$

Subsequently, by using the Panowsky-Wenzel Theorem and using a cartesian coordinate system x = acosθ, y = asinθ and ignoring con

It should be noted that Z0,0 is what is commonly referred to as the longitudinal impedance, referred to as Zlong, measured at a displacement a = 0. If we scan for different $x_0 = a$ $(\theta = 0)$ then we get :

$$Z = Z_{0,0} + x_0^2(Z_{1,1} + Z_{-1,-1} + Z_{1,-1} + Z_{-1,1} + Z_{2,0} + Z_{0,-2} + Z_{0,2} + Z_{-2,0})$$

$$= Z_{0,0} + x_0^2\left(Z_{dip_x} - Z_{quad}\right)$$

$y_0 = a$ and $\theta = \frac{\pi}{2}$: $\qquad Z = Z_{0,0} + y_0^2\left(Z_{dip_y} + Z_{quad}\right)$

Theory of Two Wire

$$Z = (2a)^2\left(Z_{1,1} + Z_{-1,-1} + Z_{1,-1} + Z_{-1,1}\right) + O(a^4)$$

$$Z_{dip_x} = \frac{Z_{1,1} + Z_{-1,-1} + Z_{1,-1} + Z_{-1,1}}{k} = \frac{c}{2\pi f}\frac{Z}{\Delta^2}$$

By applying the Panofsky-Wenzel theorem:

$$\mathbf{Z}^{\perp} = \frac{1}{k}\boldsymbol{\nabla}_2^{\perp} Z, \tag{10}$$

one obtains the transverse impedance

$$\begin{aligned}
kZ_x - \frac{\partial Z}{\partial x_2} \quad - \quad & Z_{0,1} + Z_{0,-1} + (x_1 - jy_1)Z_{1,-1} + 2(x_2 - jy_2)Z_{0,-2} \\
& + (x_1 - jy_1)Z_{1,1} + (x_1 + jy_1)Z_{-1,-1} + (x_1 + jy_1)Z_{-1,1} + 2(x_2 + jy_2)Z_{0,2} \\
& + O((x_1, y_1, x_2, y_2)^2) \\
= \quad & Z_{0,1} + Z_{0,-1} + x_1\bar{Z}_x + jy_1(-Z_{1,-1} - Z_{1,1} + Z_{-1,-1} + Z_{-1,1}) \\
& + x_2(2Z_{0,-2} + 2Z_{0,2}) + jy_2(-2Z_{0,-2} + 2Z_{0,2}) + O((x_1, y_1, x_2, y_2)^2), \quad (11)
\end{aligned}$$

$$\begin{aligned}
kZ_y = \frac{\partial Z}{\partial y_2} \quad = \quad & jZ_{0,1} - jZ_{0,-1} - j(x_1 - jy_1)Z_{1,-1} - 2j(x_2 - jy_2)Z_{0,-2} \\
& + j(x_1 - jy_1)Z_{1,1} - j(x_1 + jy_1)Z_{-1,-1} + j(x_1 + jy_1)Z_{-1,1} + 2j(x_2 + jy_2)Z_{0,2} \\
& + O((x_1, y_1, x_2, y_2)^2) \\
= \quad & j(Z_{0,1} - Z_{0,-1}) + y_1\bar{Z}_y + jx_1(-Z_{1,-1} + Z_{1,1} - Z_{-1,-1} + Z_{-1,1}) \\
& + y_2(-2Z_{0,-2} - 2Z_{0,2}) + jx_2(-2Z_{0,-2} + 2Z_{0,2}) + O((x_1, y_1, x_2, y_2)^2). \quad (12)
\end{aligned}$$

Usually one considers $\bar{Z}_x$ and $\bar{Z}_y$ only. So the transverse coupling impedance becomes $Z_x = x_1\bar{Z}_x/k$, $Z_y = y_1\bar{Z}_y/k$.

One can see that $\mathbf{J}_{-m}(\omega) = \mathbf{J}_m^*(-\omega)$, then

$$Z_{-m,-n}(\omega) = Z_{m,n}^*(-\omega). \tag{13}$$

Thank you for your Attention!