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Coupling Impedance Measurement and Analysis of Critical Vacuum Chamber Components for the APS-U

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ENERGY

Outline

1. Introduction

- Overview of APS Upgrade (APS-U)
- Motivation behind my research work
- Wakefield and impedance

2. Impedance Measurement Techniques

- Modeling of a vacuum component as a transmission line
- Traditional coaxial wire method
- The novel Goubau line method

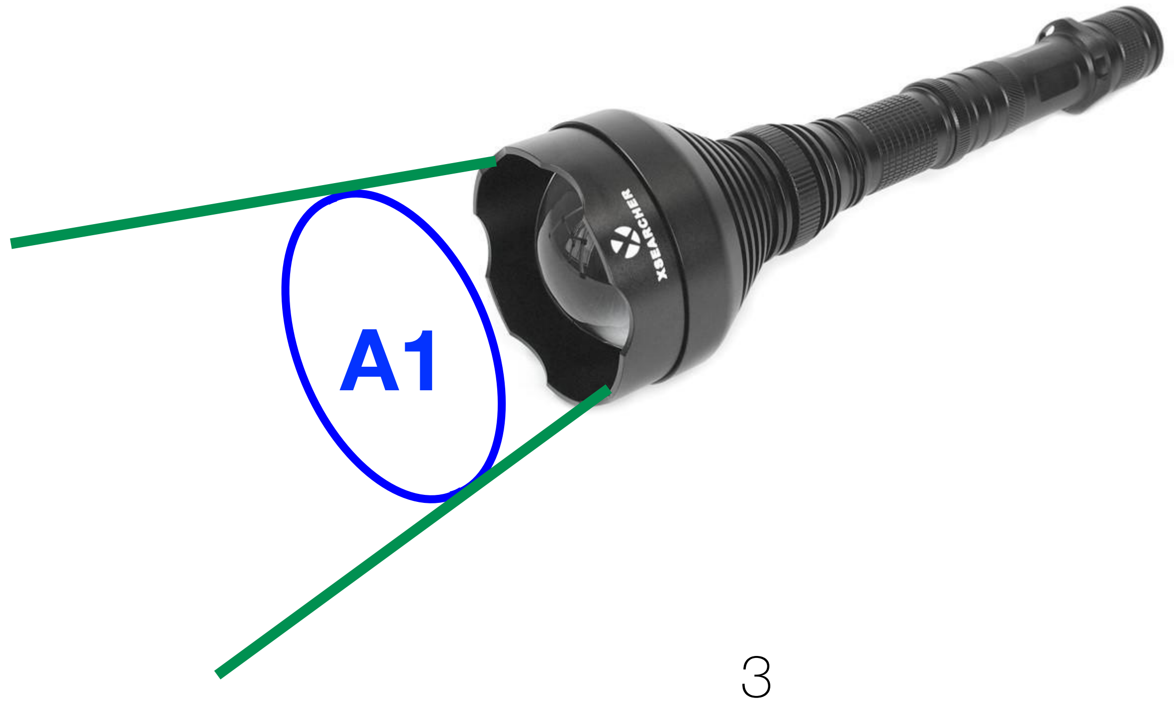
3. Results

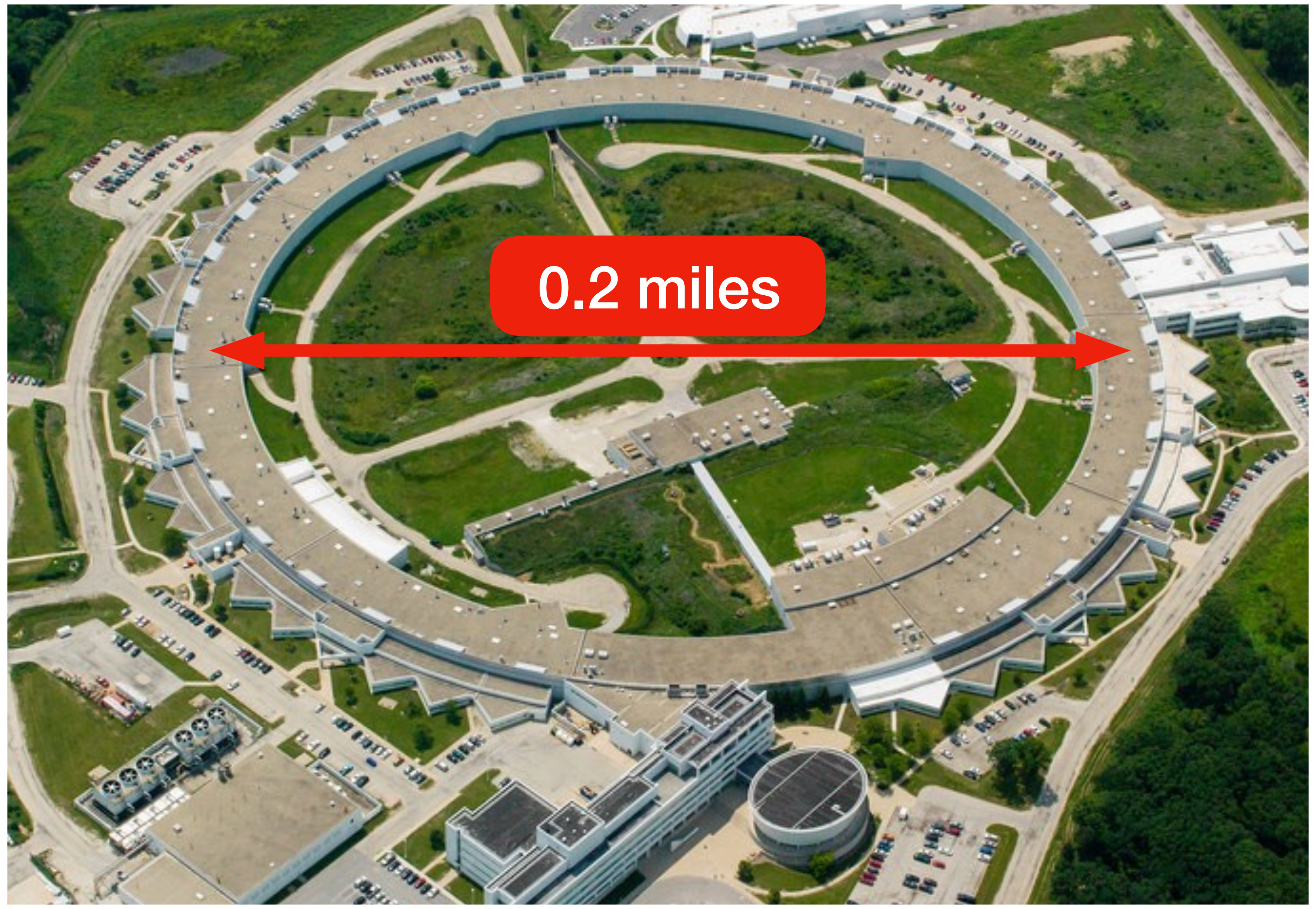
- Measurement of a NEG coated chamber
- Benchmarking of the novel Goubau line setup
- Measured results of critical APS-U vacuum chamber components
- Summary

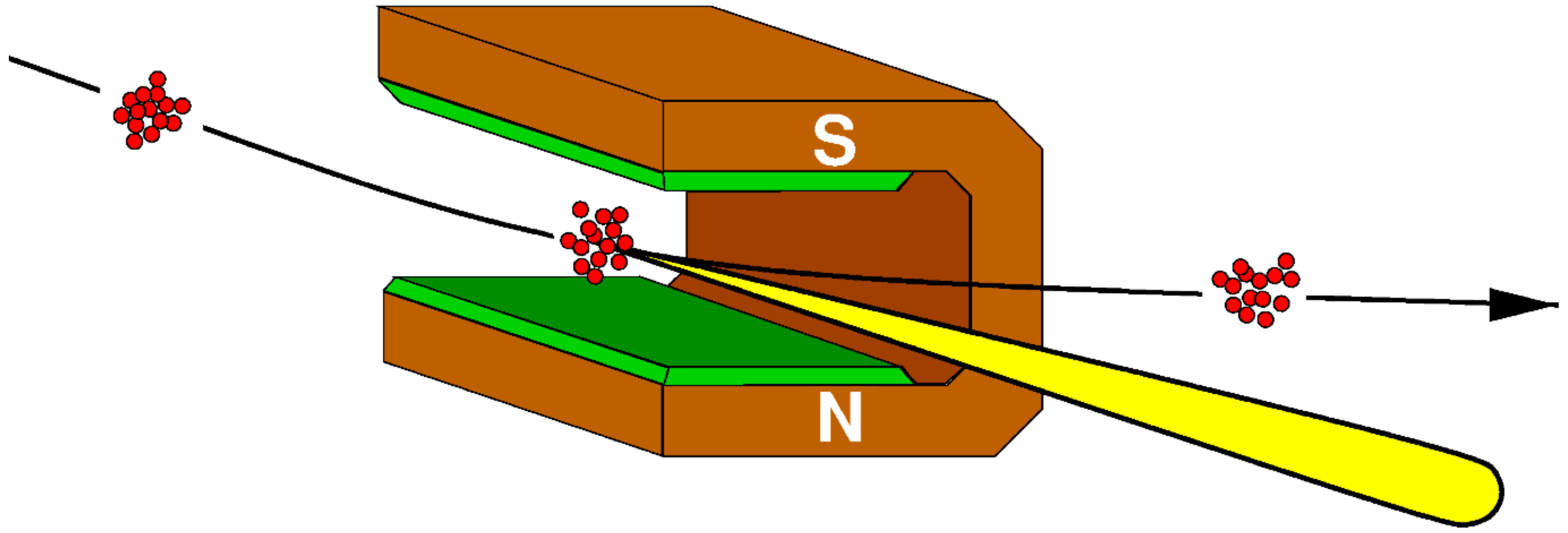
Background Information

- A relativistic charged particle such as an electron emits radiation when it moves through a curved path. This radiation is called synchrotron radiation.
- An accelerator facility that generates this type of powerful X-rays or radiation is called a storage ring.
- More than 5000 scientists/year use the APS hard x-ray facility.
- The quality of the synchrotron radiation can be characterized in terms of brightness.

$$\textbf{Brightness}(\lambda) = \frac{\textbf{Photon Flux}(\lambda)}{\textbf{Area of Phase Space (Emittance)}}$$







http://photon-science.desy.de/

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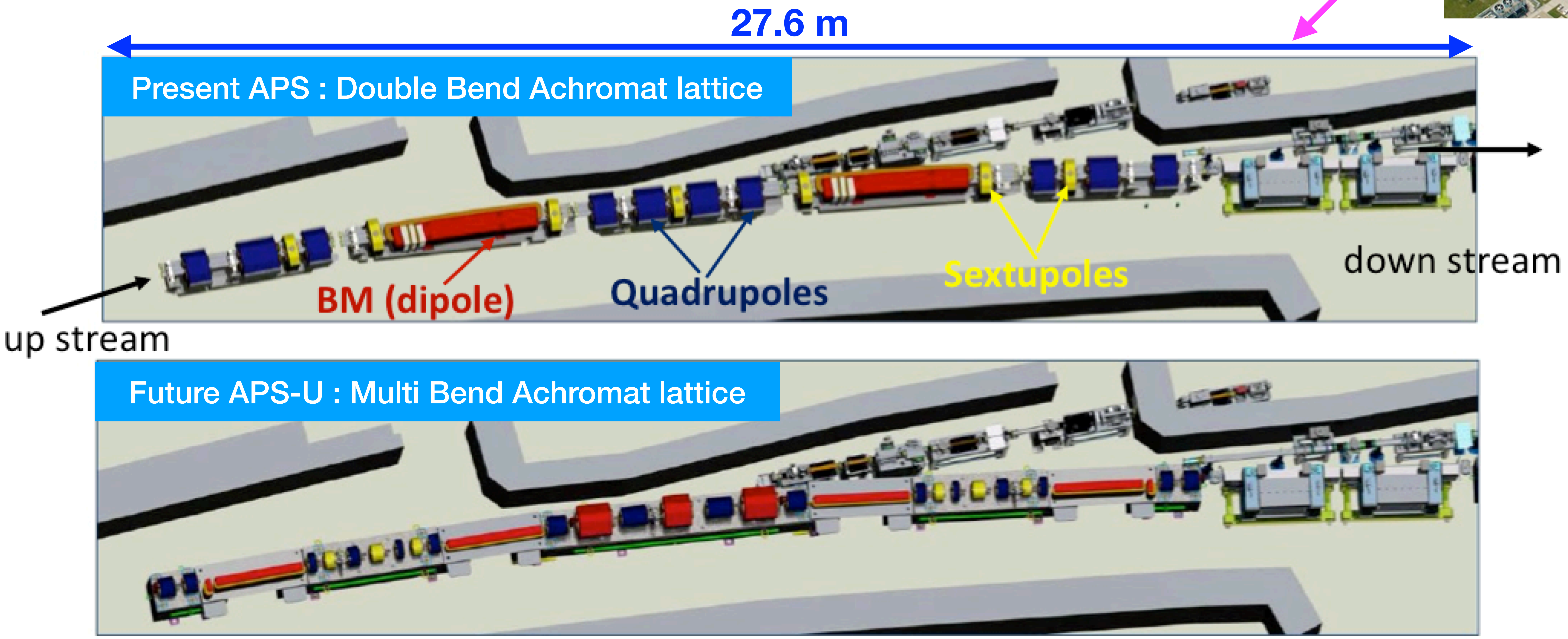
Overview of the APS Upgrade

Goal: Build the world's leading high-brightness hard x-ray storage ring.

Strategies:
- Reduce the APS emittance by incorporating a "fourth generation" MBA lattice.
- Install next generation super conducting undulators.
- Develop world class very stable beam lines.



$$\text{Emittance} \propto \frac{E^2}{N_d^3}$$

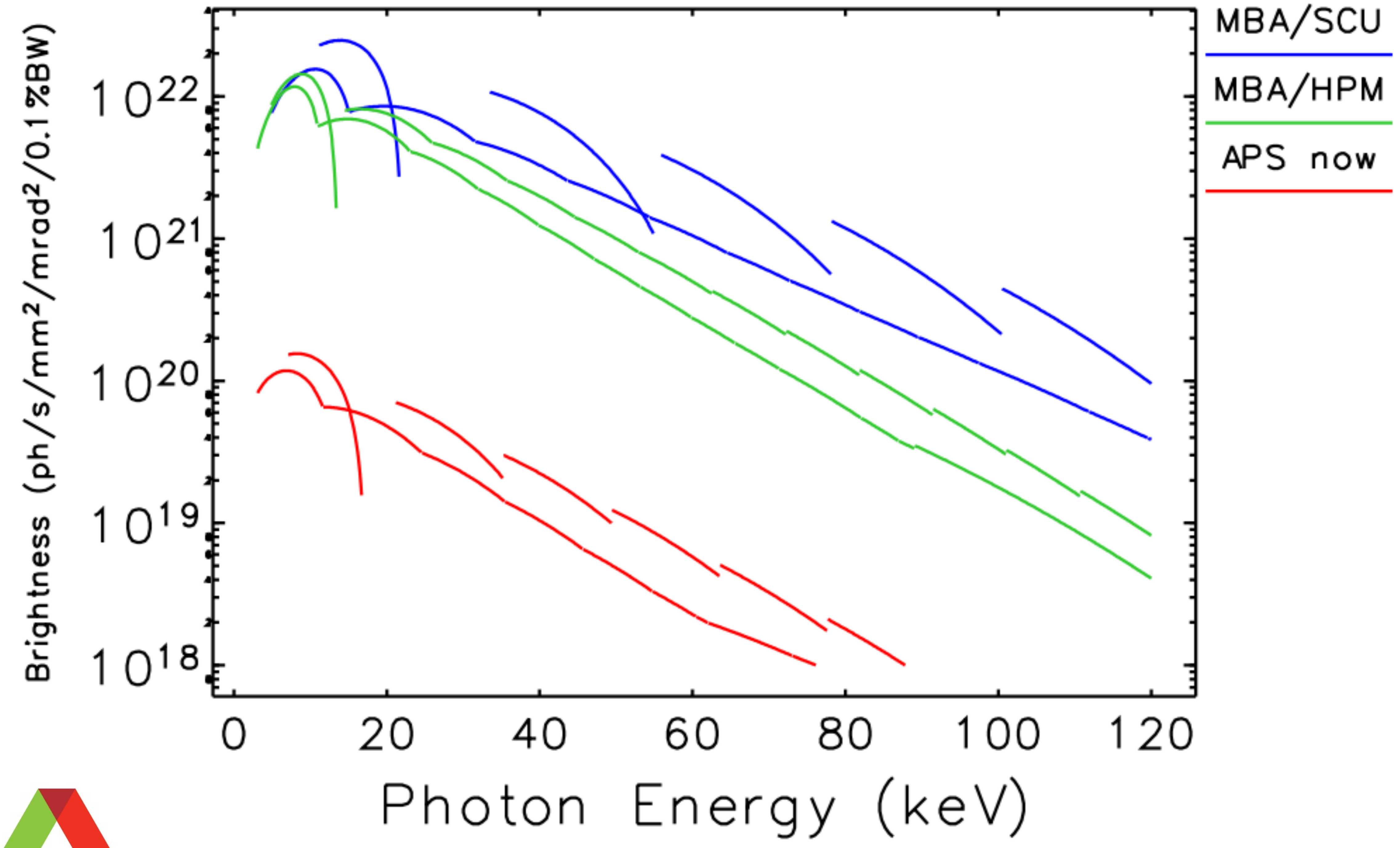
E = Energy
N_d = # of dipoles

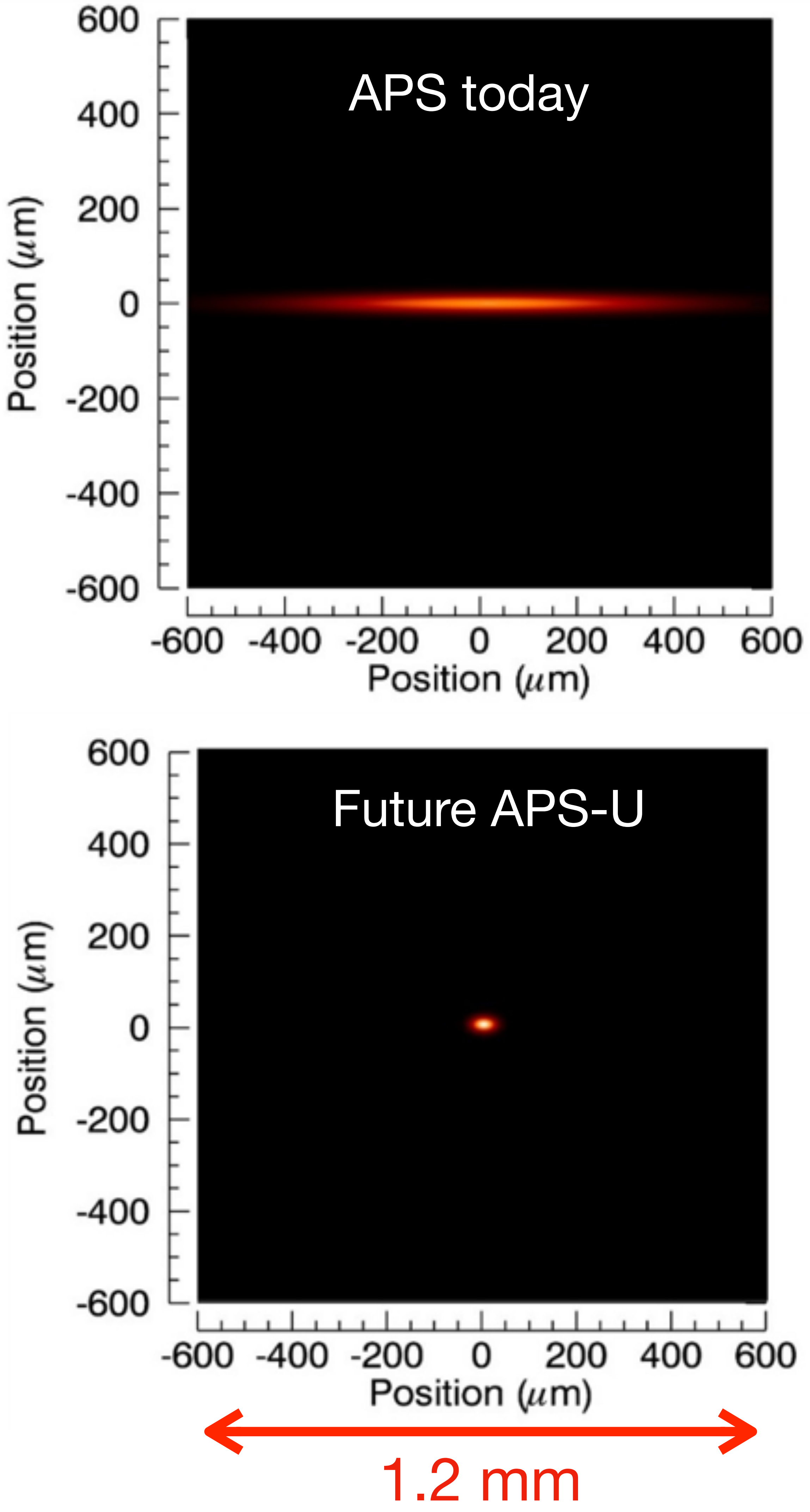
3200 pm-rad → **~42 pm-rad**

Overview of the APS Upgrade

In summary, the APS-U provides;

1. Reduction of emittance by a factor of ~100 and installation of superconducting undulators, and
2. Generation leap in storage ring performance with a factor of 100 -1000 increase in brightness and coherence flux.





Motivation Behind the Impedance Measurement

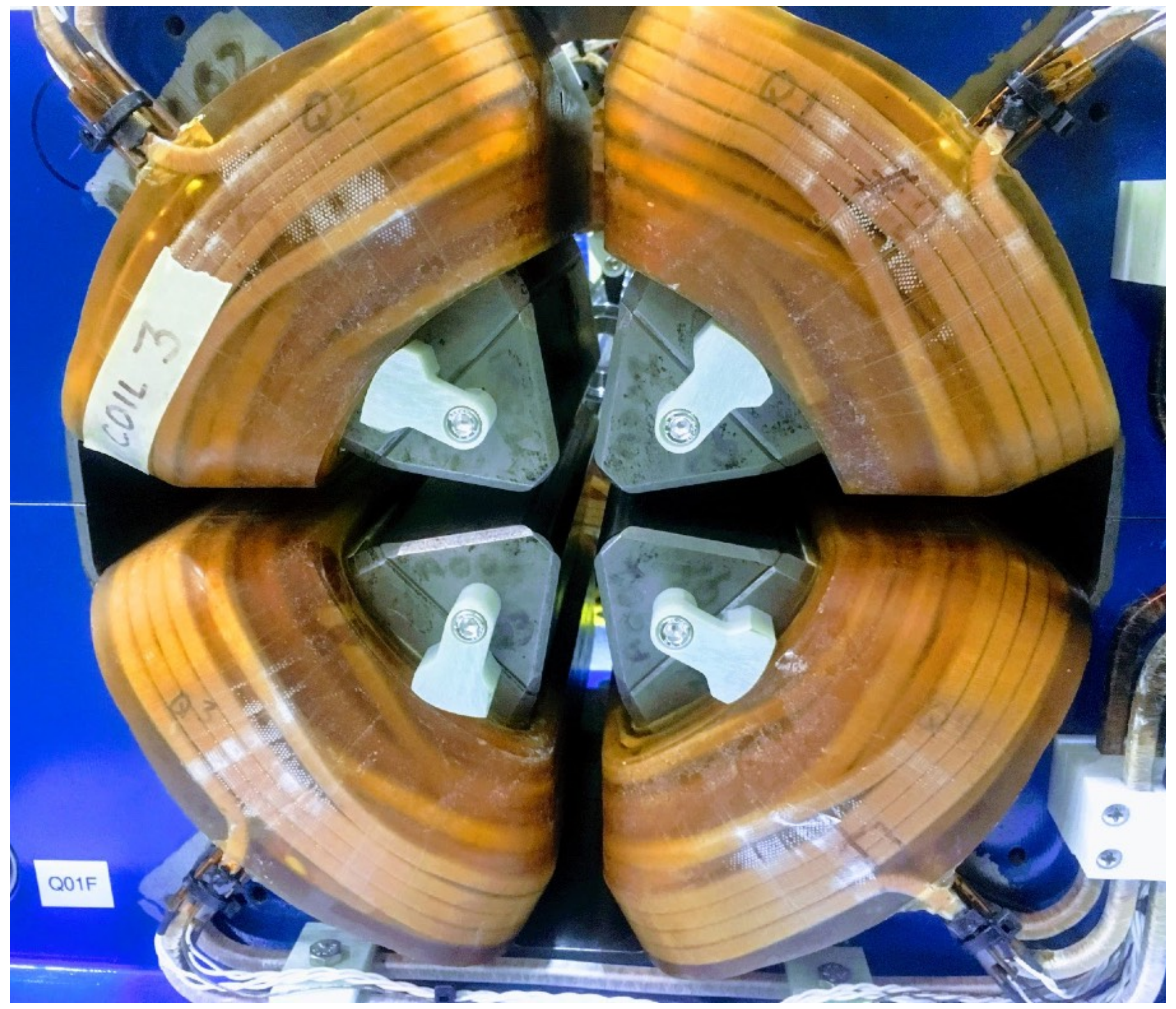
APS-U requires stronger magnets → Narrow-gap vacuum chamber → Various collective effects

characterized by → **Impedance Measurement**

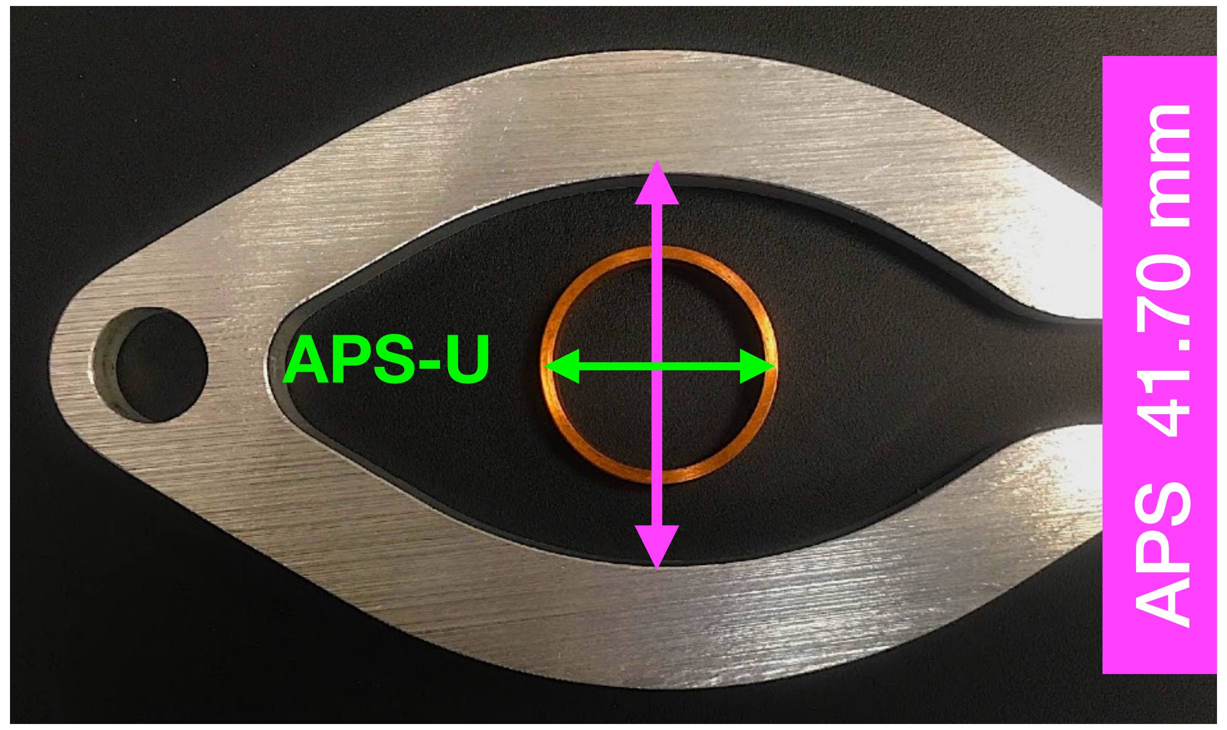
Most vendors may not have RF-Engineers (should be tested by APS) → **Impedance Measurement**

Simulation codes exists → Seems disagreement between measurements and simulations → **Impedance Measurement**

Simulation involves ideal geometry → **Impedance Measurement**



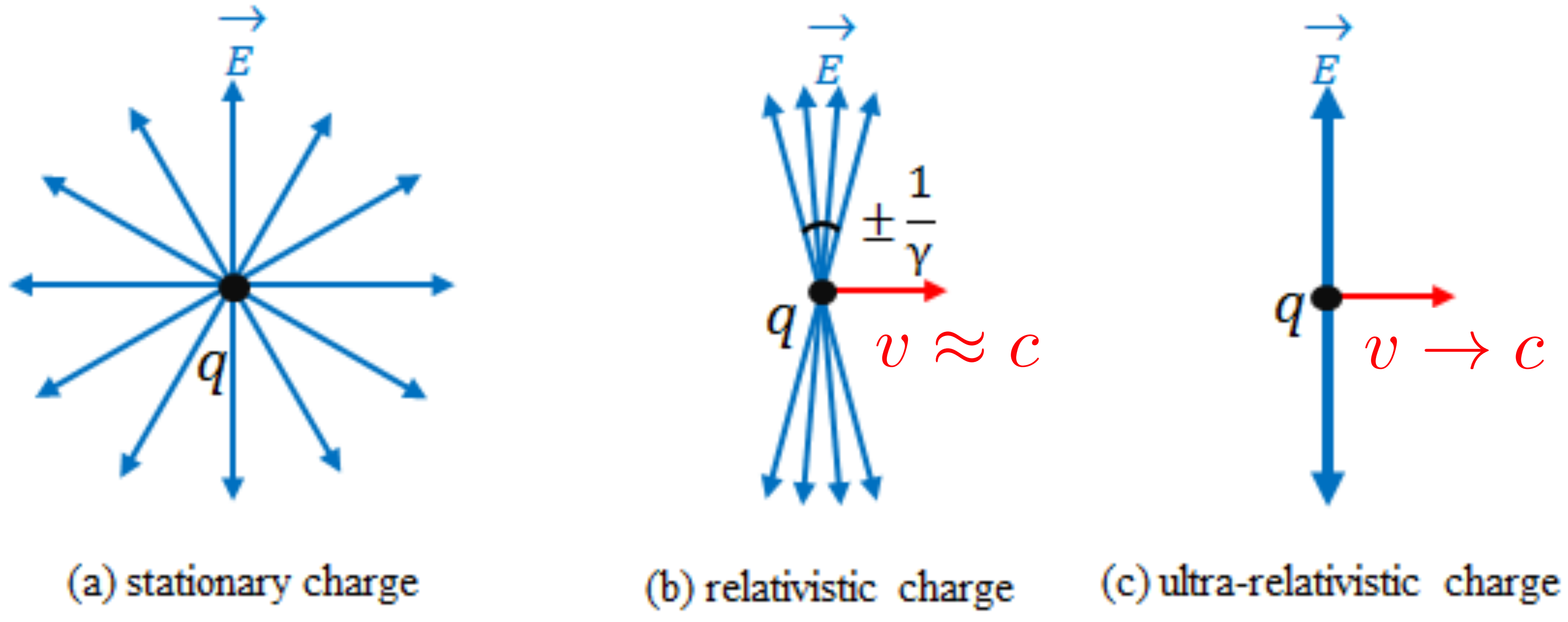
APS-U Quadrupole

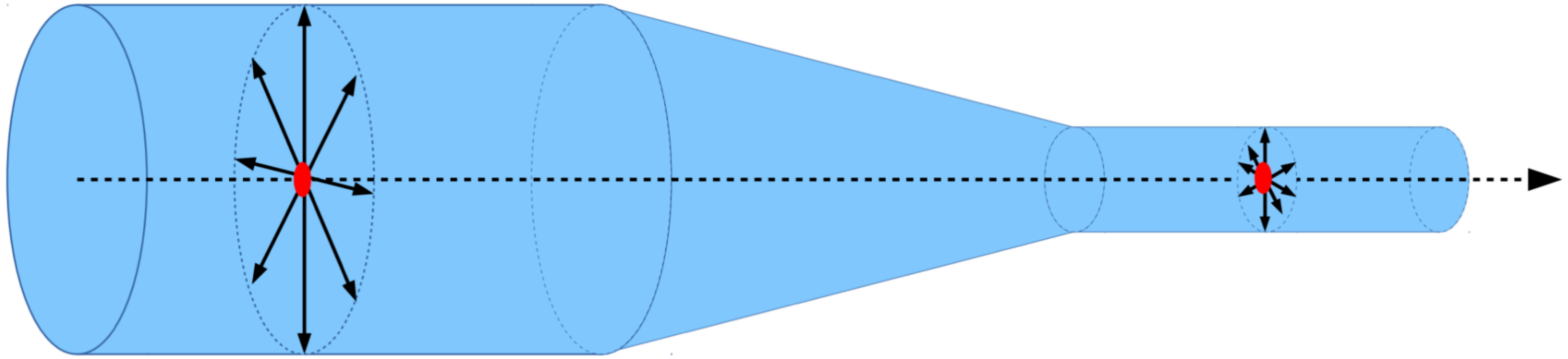


Vacuum chamber cross section comparison

Wakefields and Impedances

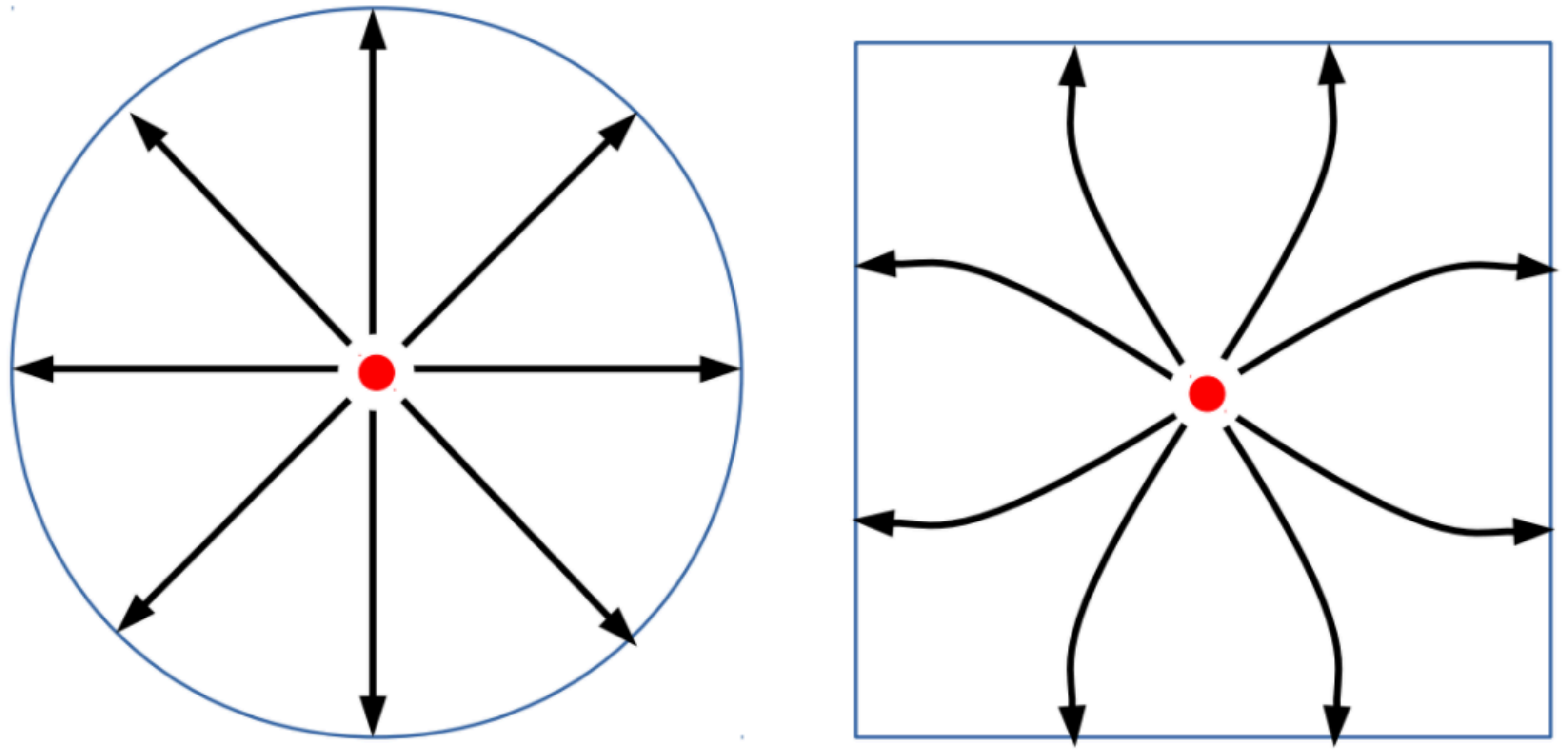
- The Coulomb field of a relativistic electron appears “flattened” into a pancake shape.
- These fields must also satisfy boundary conditions on vacuum chamber walls.
- The new boundary conditions result in EM fields behind the exciting electron (since v ~ c) which are called wakefields.





Changes in vacuum chamber cross section → Rearrangement of fields to satisfy new boundary conditions

Field lines can be arranged to satisfy appropriate boundary conditions for arbitrary geometries



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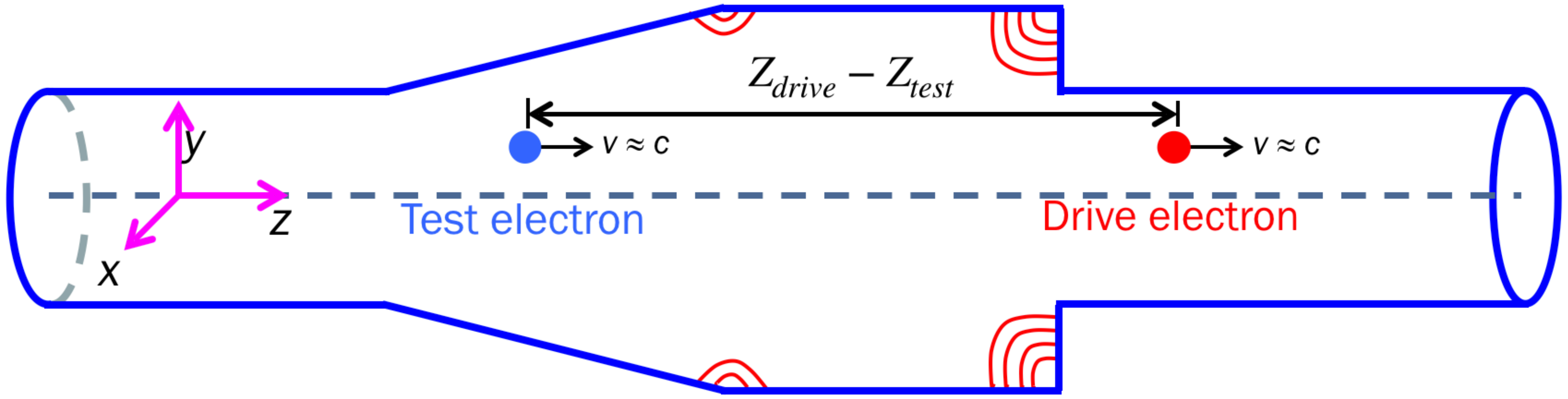
Wakefields and Impedances



- The test electron energy changes because of the EM fields of drive electron. This energy change can be characterized in terms of wakefields.

$$\Delta\gamma = -\frac{e}{mc^2}\int_{-\infty}^{\infty} ds E_z \equiv -\frac{e^2}{mc^2} W_{\parallel}(x, y, z)$$

energy change **wakefield**

- The strength of wakefields depends upon the conductivity and the cross-section variation of the chamber.

- The Fourier transform of the wakefield is called the impedance.

$$Z_{\parallel}(\omega) = \frac{1}{c}\int d\xi e^{i\omega\xi/c} W_{\parallel}(\xi)$$

$$\xi = z_{drive} - z_{test}$$

$$\text{Impedance}(Z_{\parallel}) \propto \frac{1}{\text{beam pipe radius}}$$

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Effects of Longitudinal Impedance

Impedance type	Causes	Effects
Broad band impedance (short term wakefield)	• Heating of vacuum chamber components due to energy loss • Bunch lengthening • Microwave instability	• Component damage • Increase in energy spread (not a severe effect)
Narrow band impedance (long term wakefield)	• Heating of cavities • Multi-bunch instabilities	• Increase in emittance

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- Traditional coaxial wire method
- The novel Goubau line method

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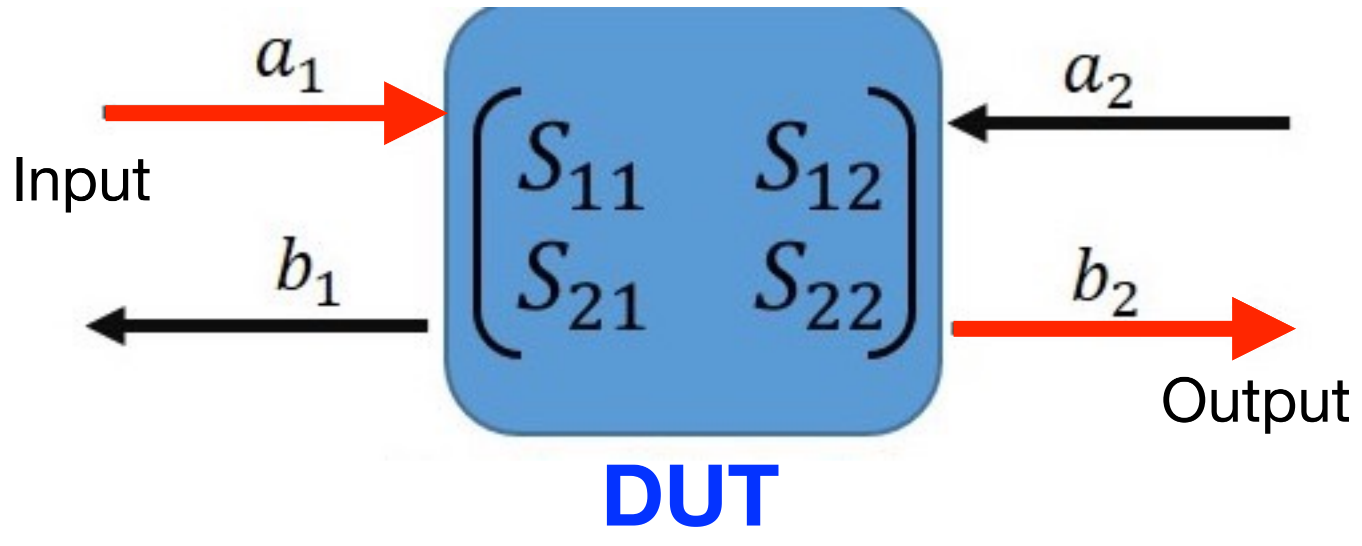
Impedance Measurement: Modeling a Vacuum Component as a Transmission Line

- We model the device under test (DUT) as a two port transmission line, and measure its insertion loss (S_{21}-parameter).



We measure

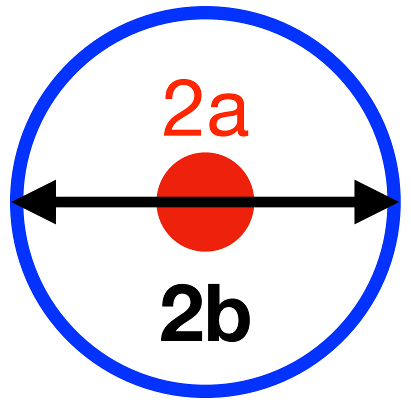
$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \qquad S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0}$$

- By measuring the S_{21}-parameters for the DUT and a corresponding reference pipe (REF), we can calculate the impedance of the DUT using appropriate formula.

$$Z_{\parallel}^{HP}(\omega) = 2Z_c\left(\frac{S_{21}^{REF} - S_{21}^{DUT}}{S_{21}^{REF}}\right)$$

Lumped impedance

$$Z_c = 60\ln\left(\frac{b}{a}\right)$$



$$Z_{\parallel}^{log}(\omega) \approx -2Z_c\ln\left(\frac{S_{21}^{DUT}}{S_{21}^{REF}}\right)$$

Distributed impedance

- H. Hahn and F. Pedersen, BNL 50870 ,1978.
- L.S. Walling and et. al., Nucl. Instrum. Methods Phys. Res., Sect. A281, 433 (1989).

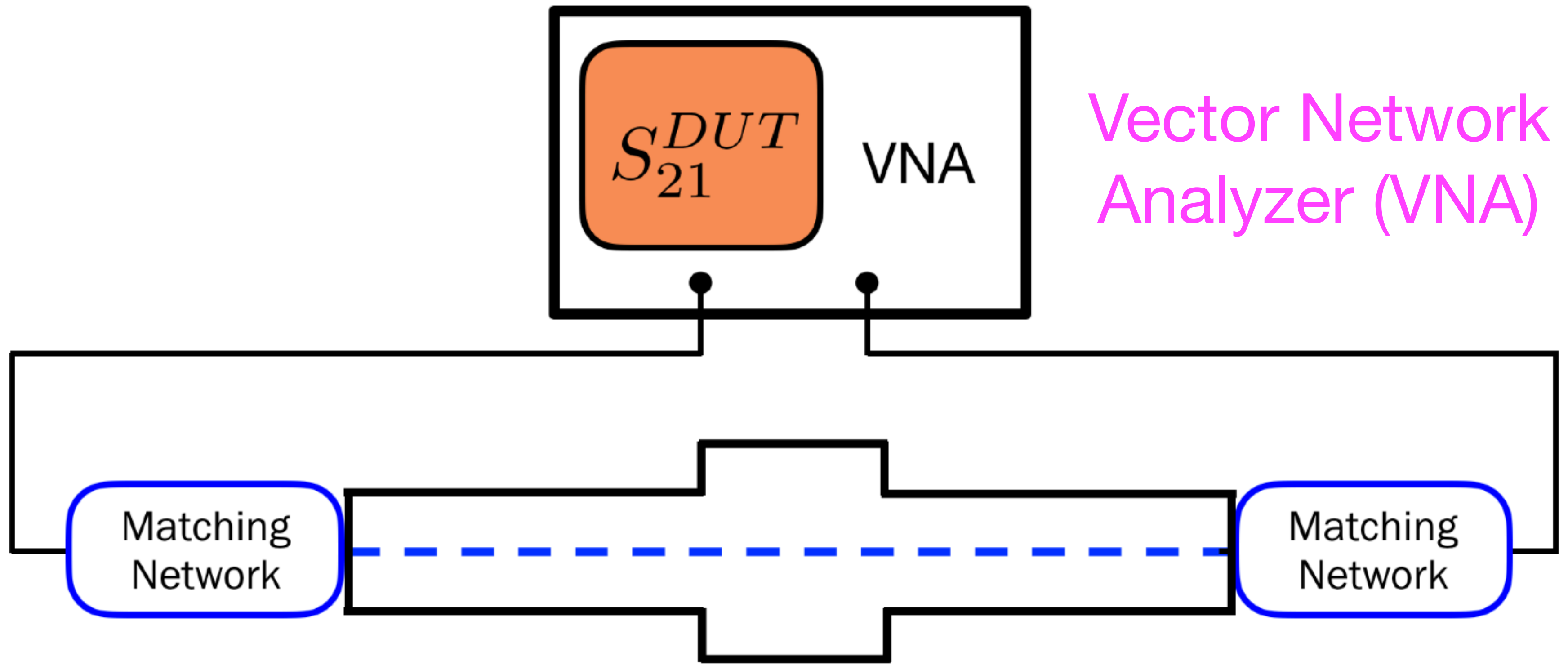
Impedance Measurement Methods

1. Traditional coaxial wire method

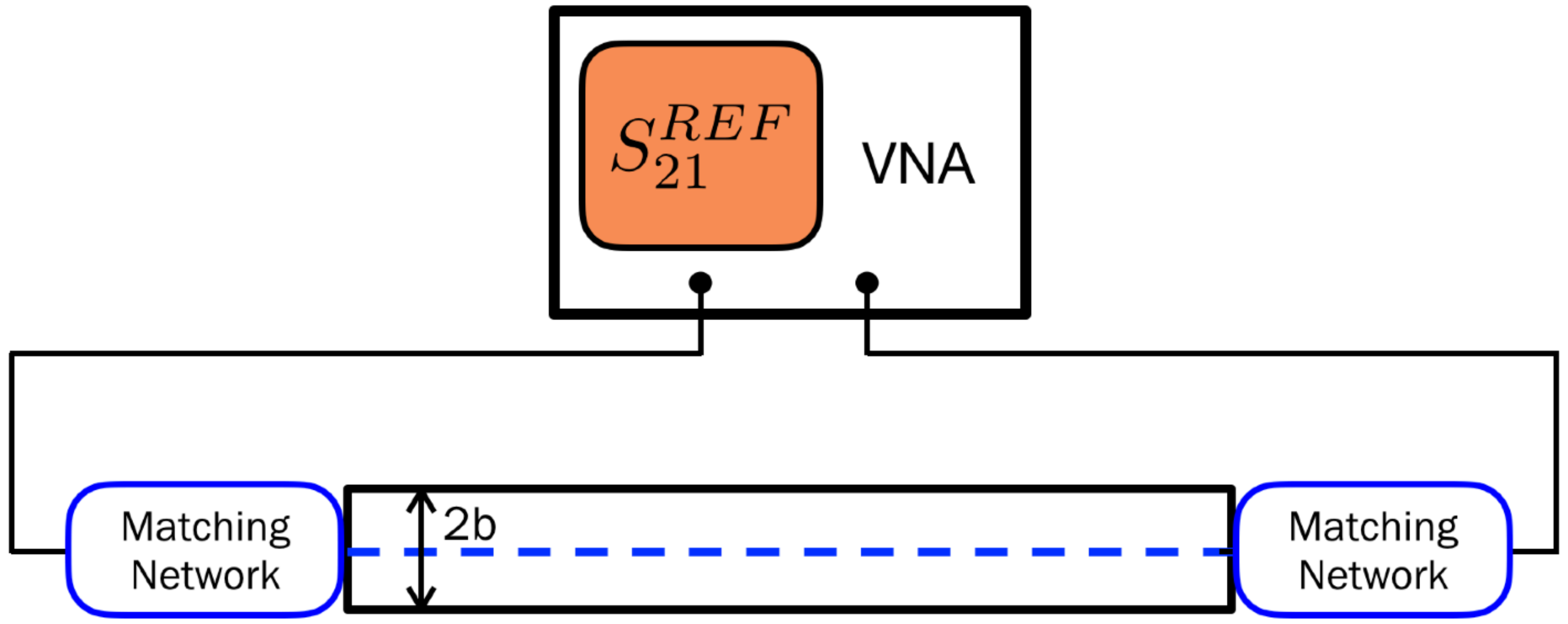
- TEM mode of coaxial cable represents Coulomb field of a particle beam.
- Gives better results mainly at lower frequencies.

Limitations:

1. Matching network complicates bench setup.
2. Large central conductor produces more perturbation to boundary conditions (less accurate beam profile).
3. Passive circuits (resistors/inductors) behave differently at high frequency.
4. Limited to narrow band measurements due to frequency range of active devices (balun and transformer) used for impedance matching.



Device Under Test (DUT)



Reference Pipe (REF)

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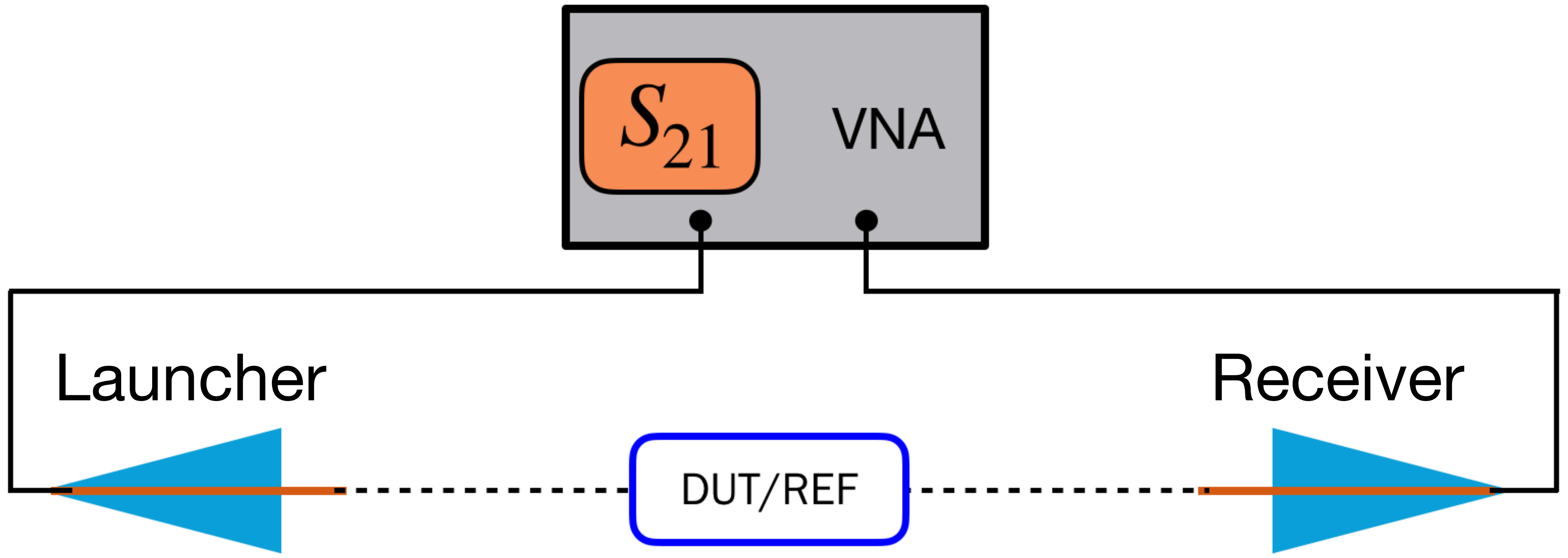
Impedance Measurement Methods

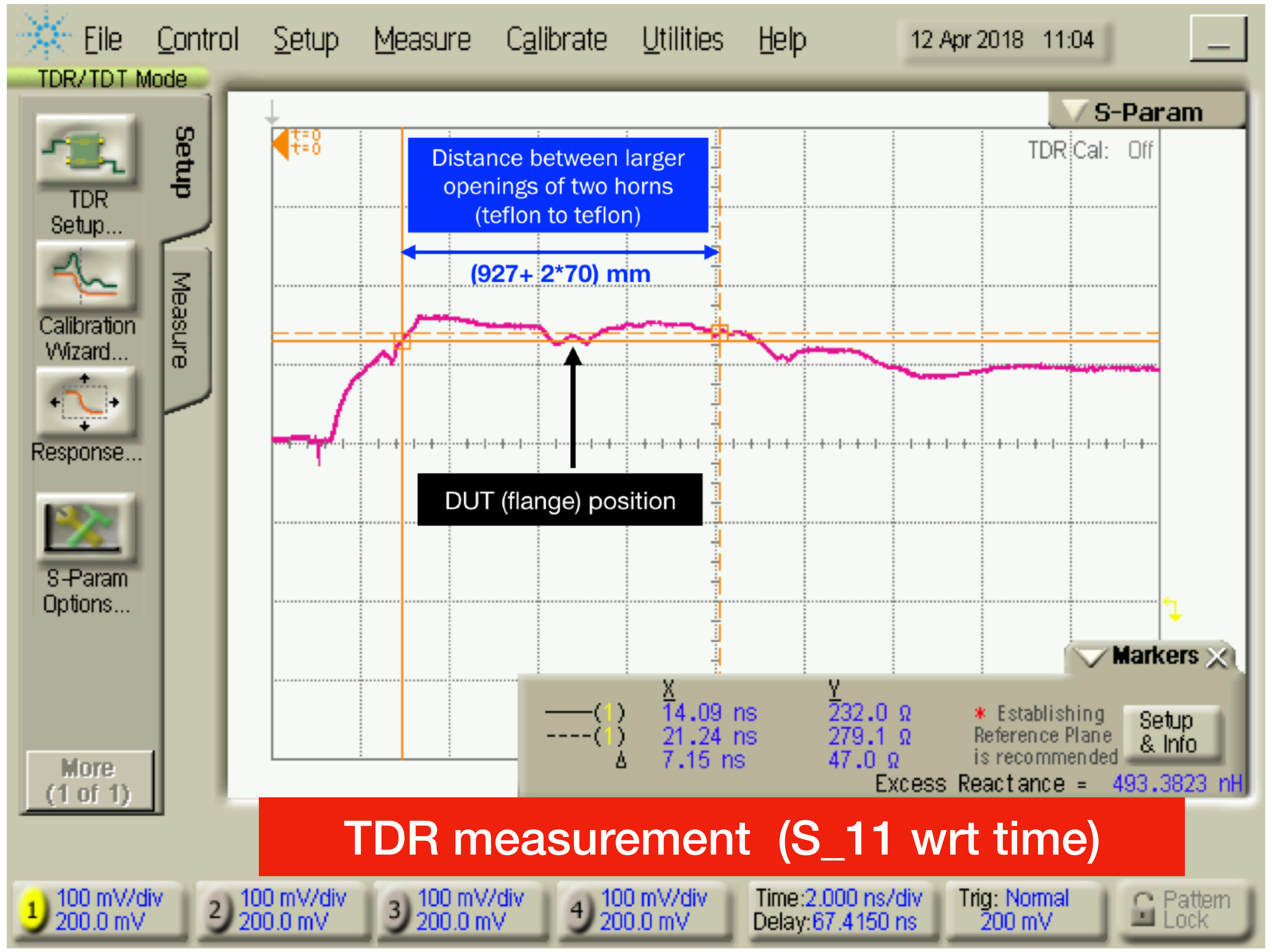
2. The novel Goubau line (G-line) setup

- Fundamental TM mode of a surface wave mimics the Coulomb field of the particle beam*.
- Gives better results at higher frequencies.
- We are among the first to use the G-line for the impedance measurement.



Advantages:

I. Does not require complicated matching network, simple setup.
II. Provides more accurate impedance matching.
III. Perturbs boundary condition less due to micron-sized wire.
IV. Enables wide band measurement.
V. Empowers quick data acquisition.



Limitation:

- Challenging to setup for a long structure.

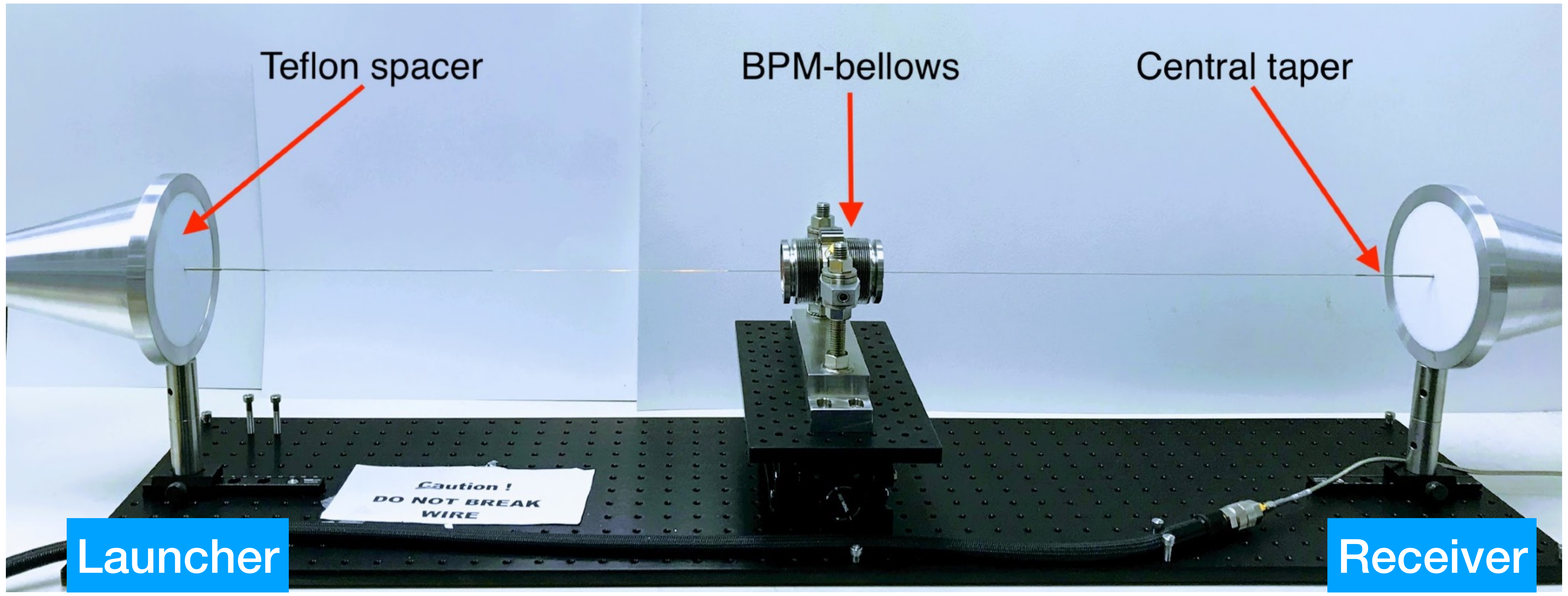
J*. Musson, K. Cole, and S. Rubin, "Application of Goubau Surface Wave Transmission Line for Improved Bench Testing of Diagnostics Beamline Elements, PAC, 2009.

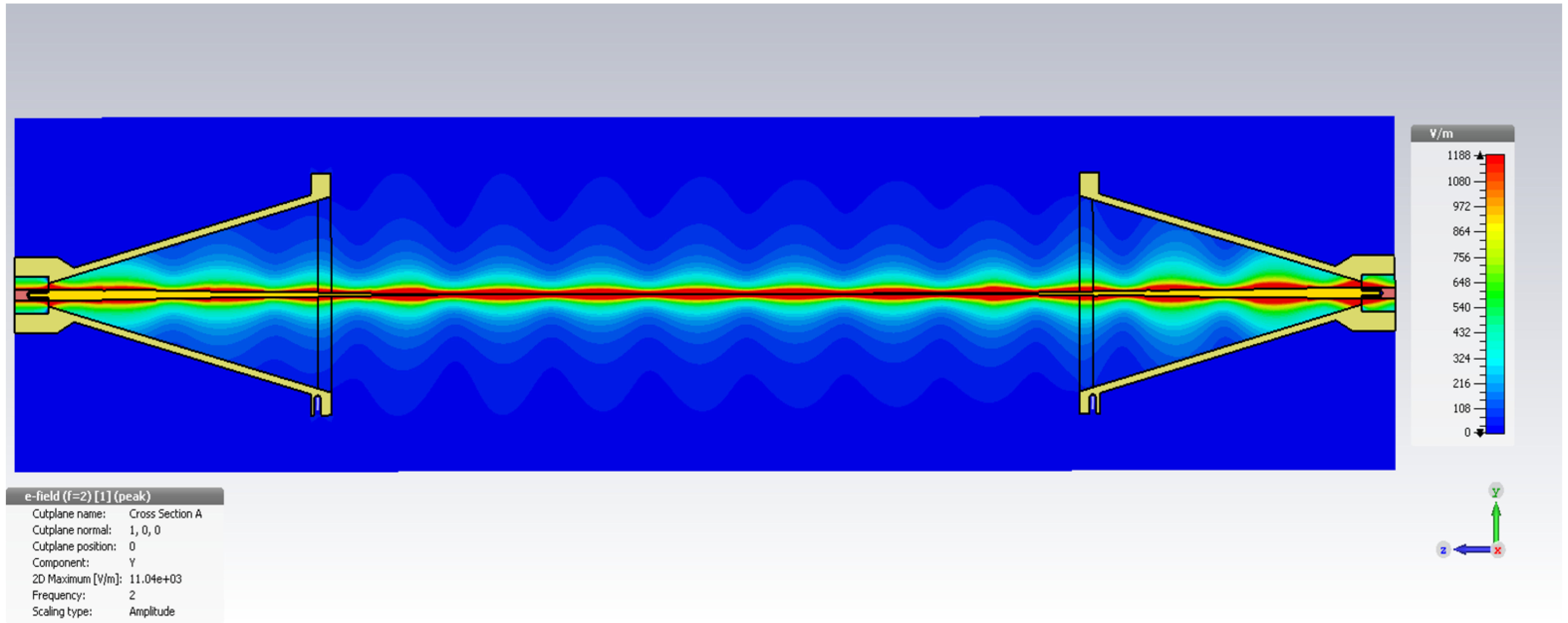
Goubau Line (G-line)

- The Goubau line is a dielectric coated single wire transmission line that works on the principle of Sommerfeld like electromagnetic surface wave*.

- The fundamental TM mode close to the dielectric coated wire resembles the EM properties of particle beam in an accelerator.

*G. Goubau, “Surface waves and their Application to Transmission Lines”, J. Appl. Phys.1950.





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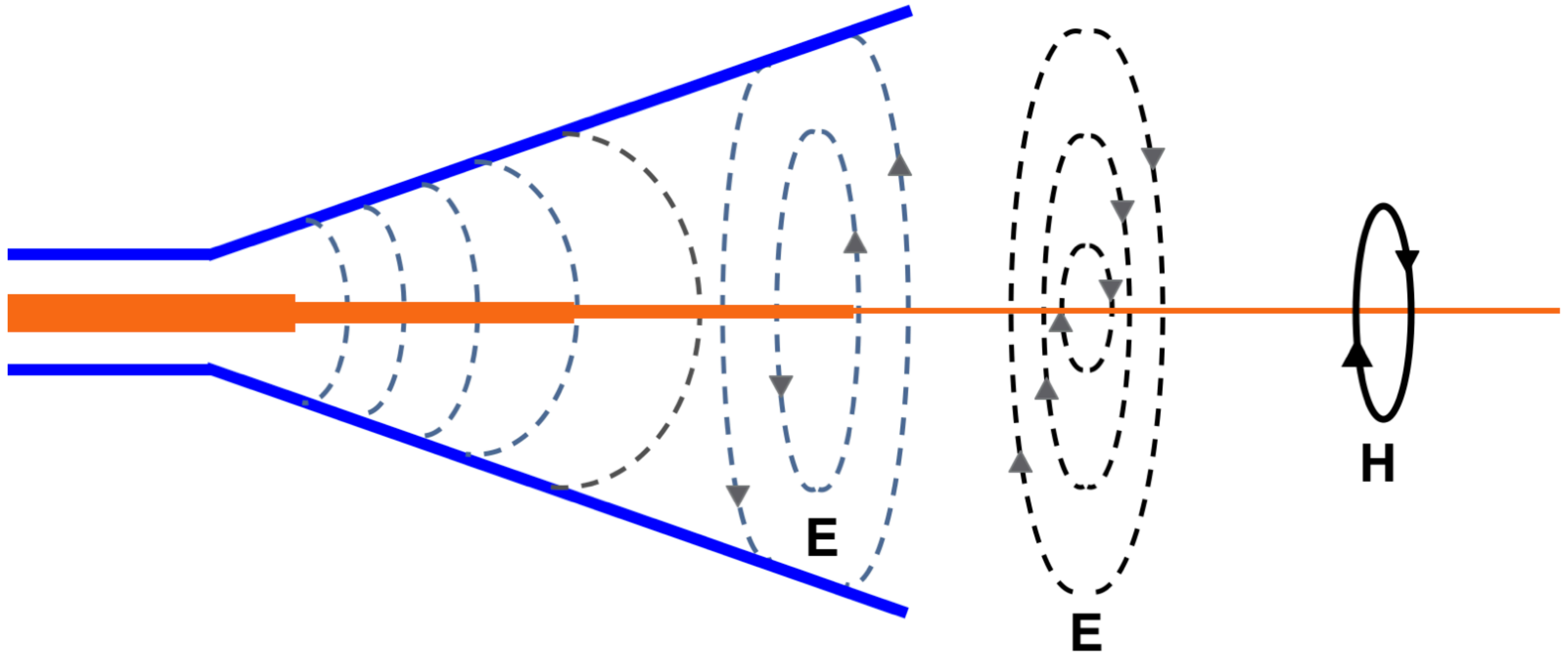
Excitation of the Surface Wave

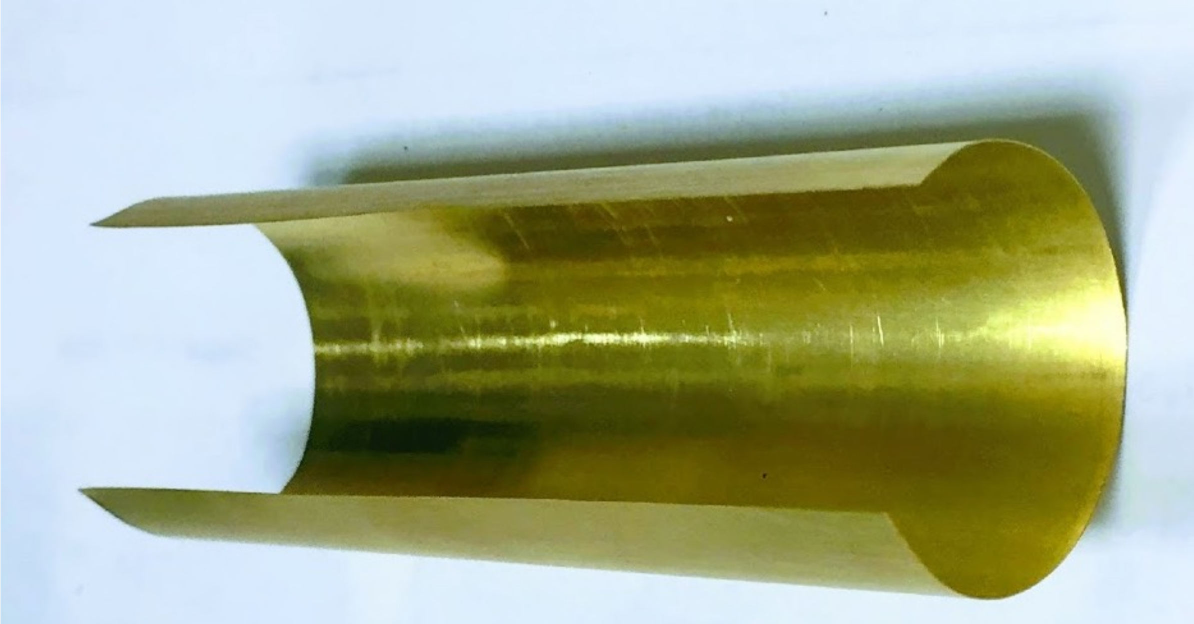
- Excitation of the fundamental TM mode to the single wire, and impedance matching from coax to the wire is done by a launcher or horn.
- A coaxial line from the vector network analyzer (VNA) supplies the excitation energy at a certain frequency.



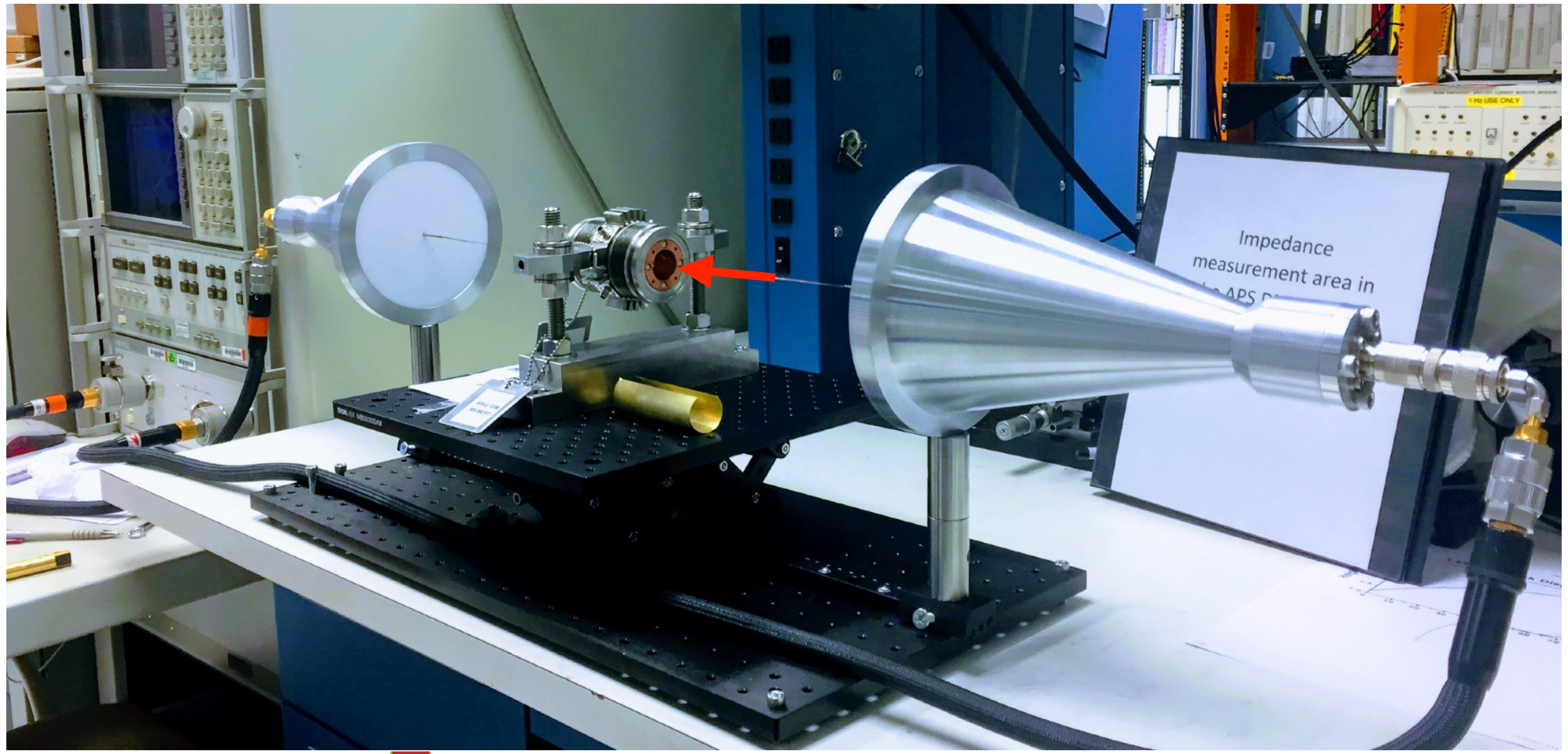
Cartoon to represent how the surface wave evolves from the G-line cone

Experimental Measurements Procedure

1. Adjust the DUT position to place the wire at its center.
2. Insert a brass sleeve into the DUT.
3. Calibrate the VNA (flat S_{21}-signal).
4. Carefully remove the brass sleeve.
5. Record the data.

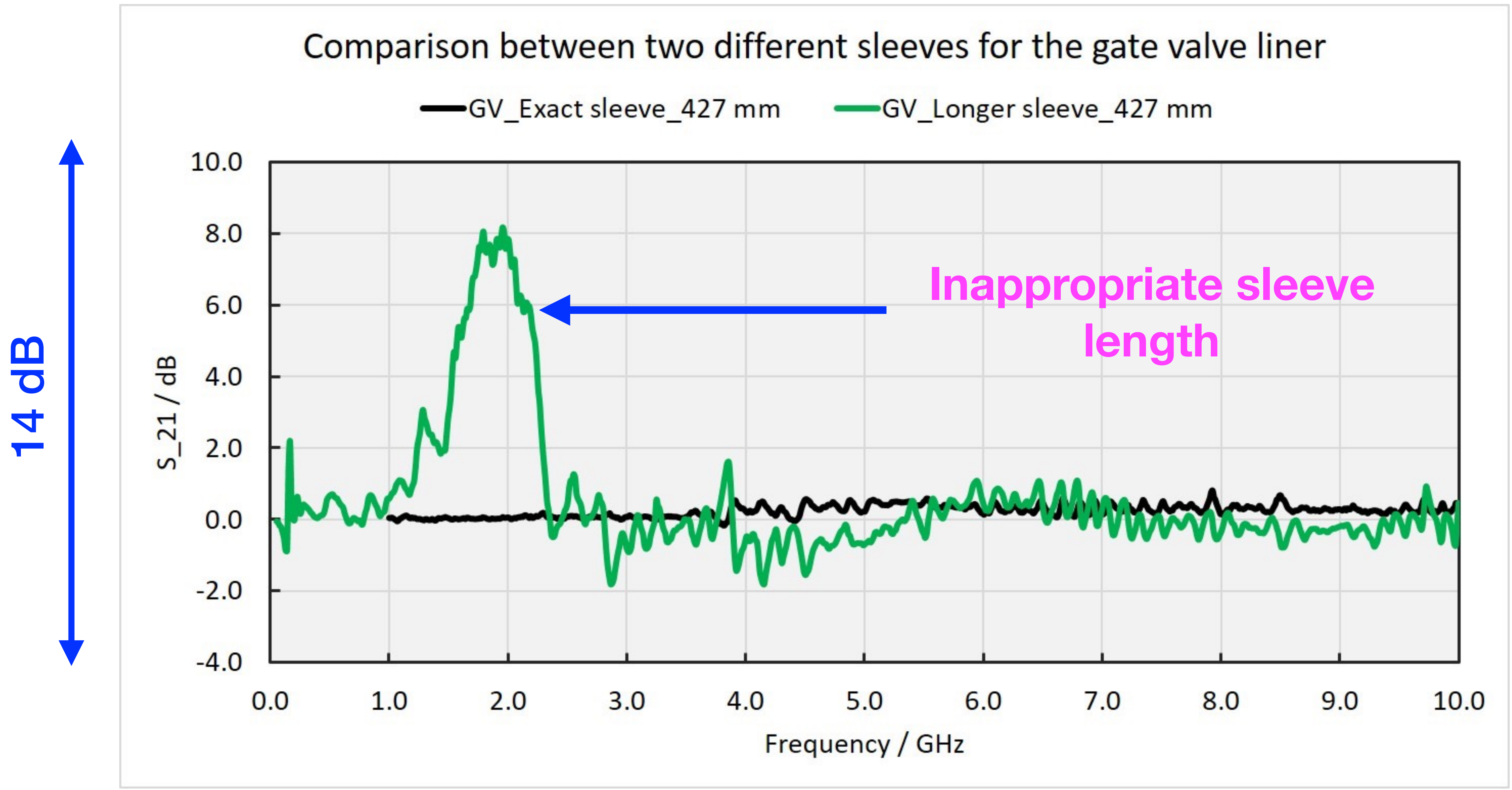


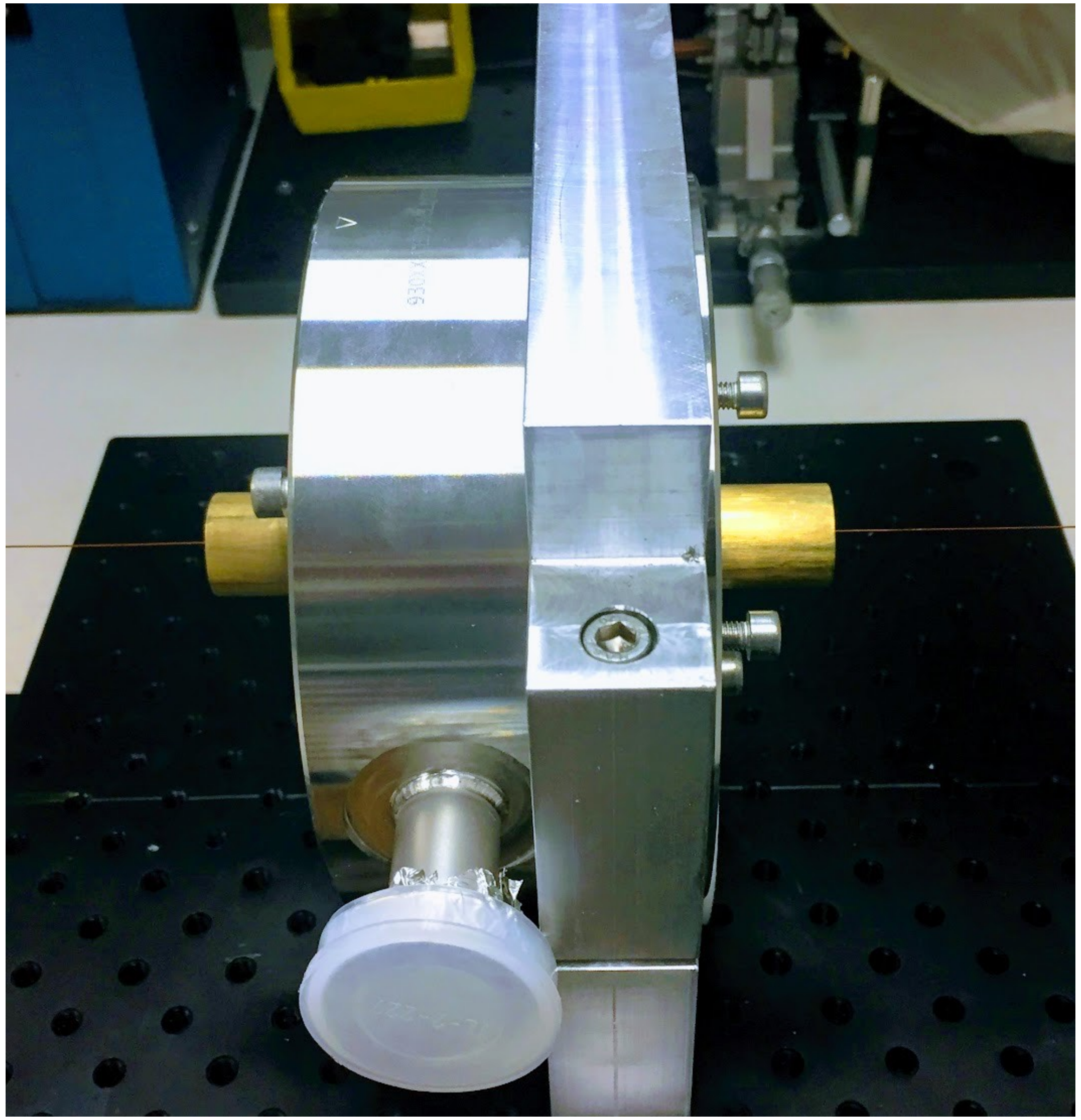
Brass sleeve



Two Important Findings

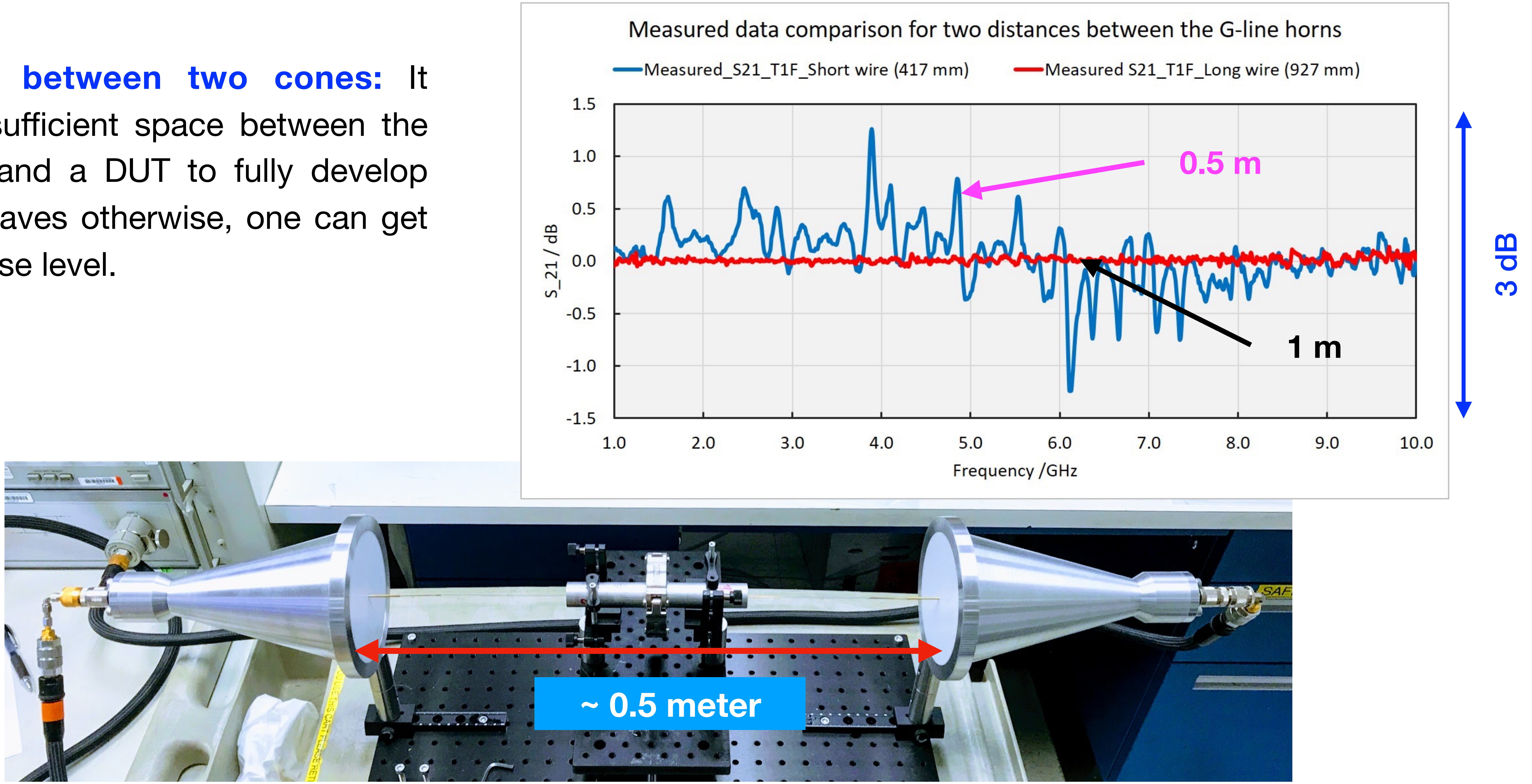
I. **Appropriate sleeve length:** It is crucial to have the REF sleeve length either equal to or less than that of DUT length. The Initial plan was to use the same sleeve for all components but, we got some weird results because of it.





Two Important Findings

II. Distance between two cones: It requires sufficient space between the launcher and a DUT to fully develop surface waves otherwise, one can get higher noise level.



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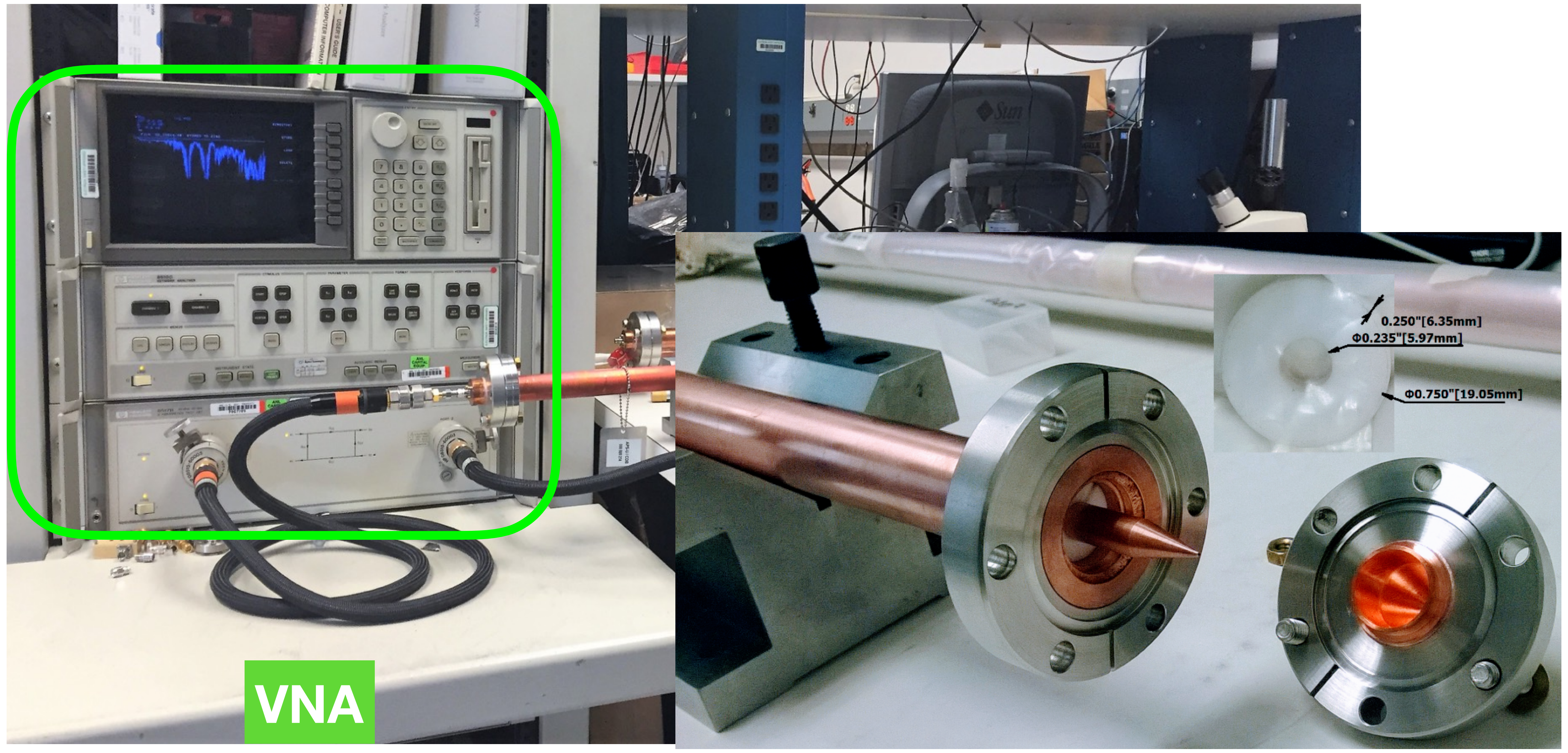
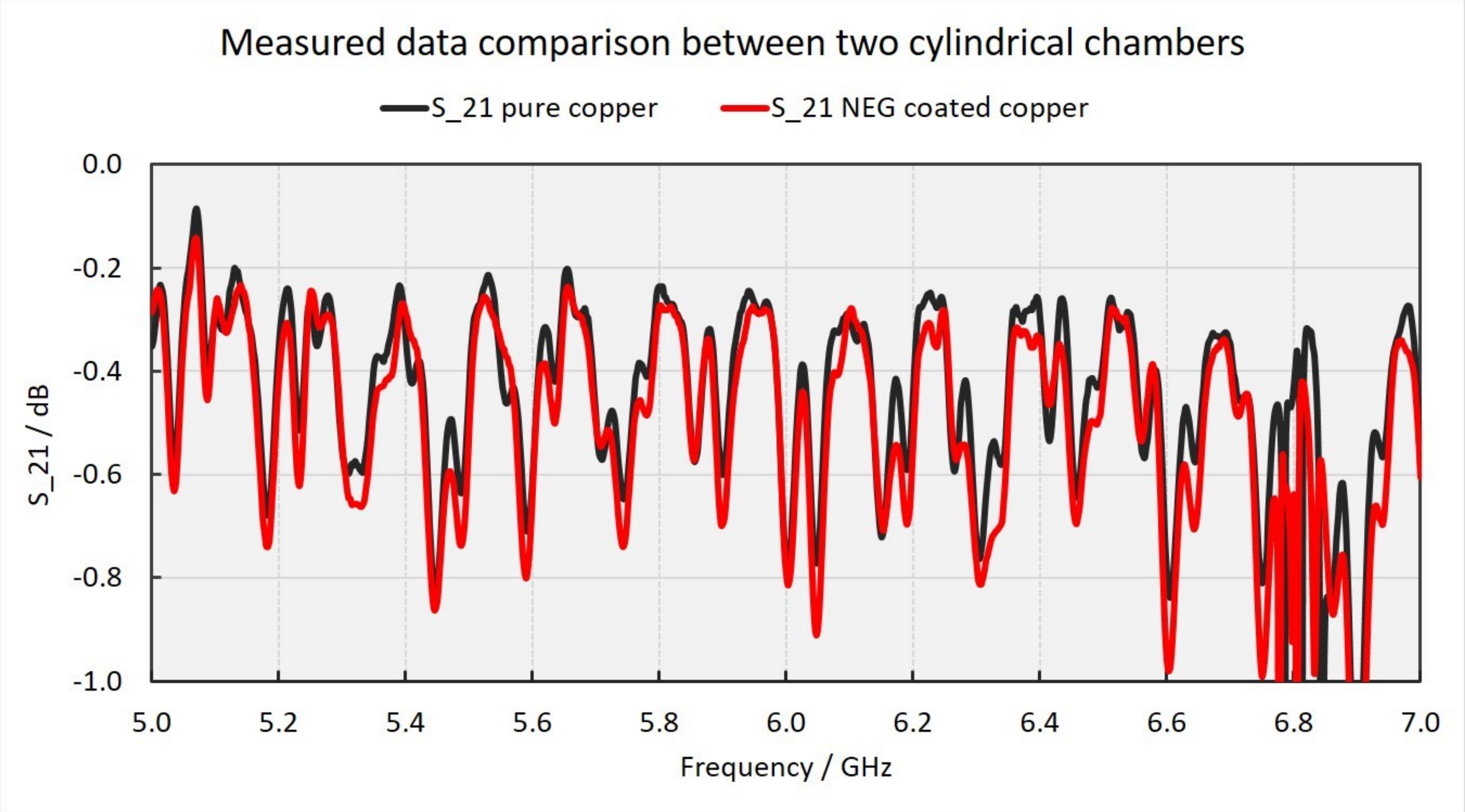
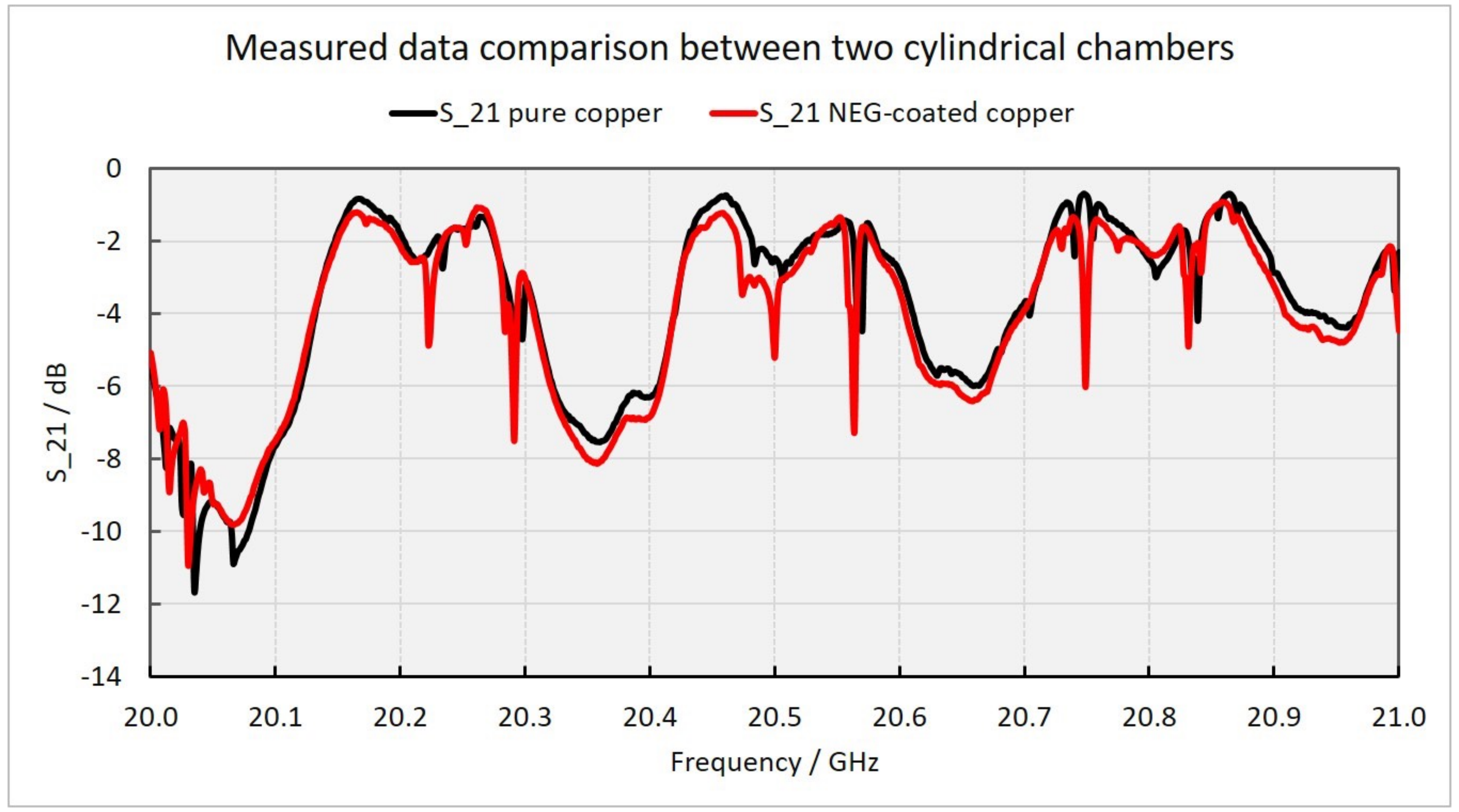
Measurement of NEG-coated Copper Chamber using traditional coaxial wire method

- Non Evaporative Getter (NEG) primarily provides distributive pumping and also reduces photon simulated desorption.
- Conductivity of micron size NEG-coating is not well characterized yet.



- Measured results showed the effect of the impedance due to the 1.5-micron thick NEG-coating is negligible below 29 GHz.





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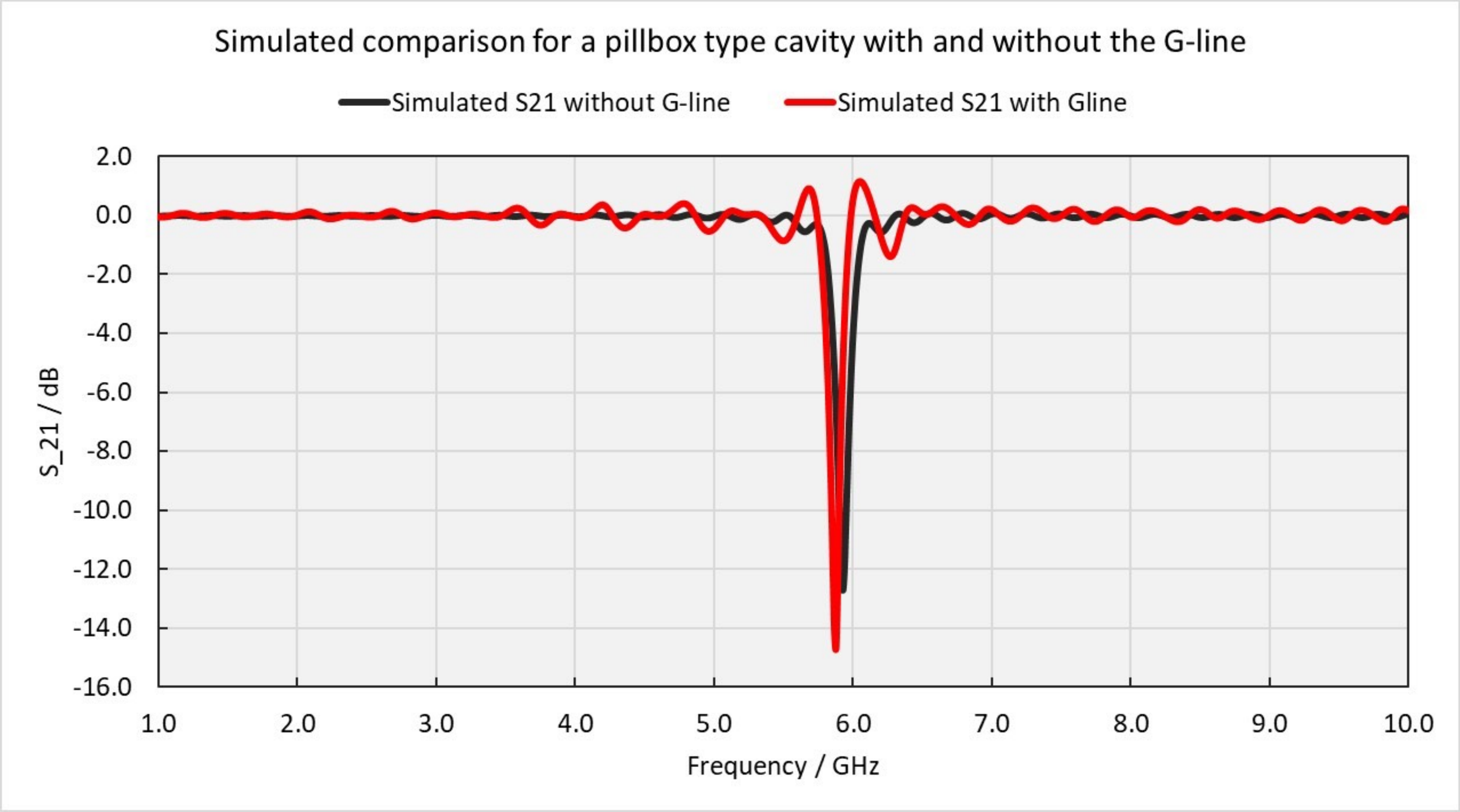
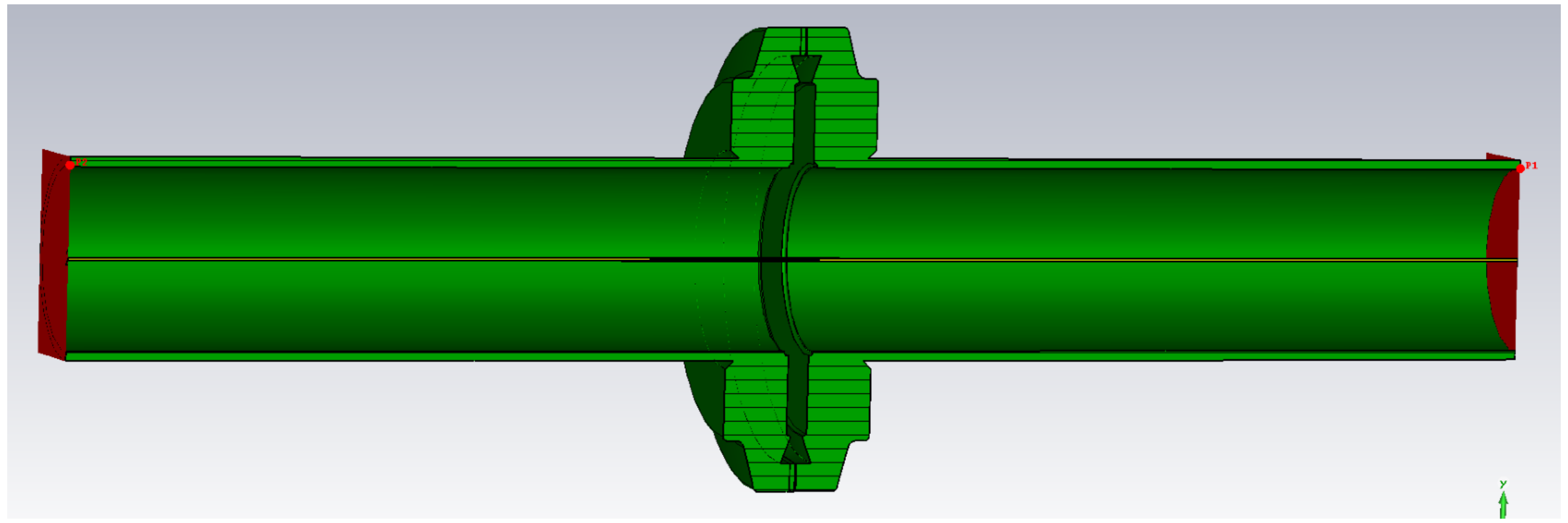
M. Sangroula and et.al,, in Proc. IPAC17 Copenhagen, Denmark, WEPVA134

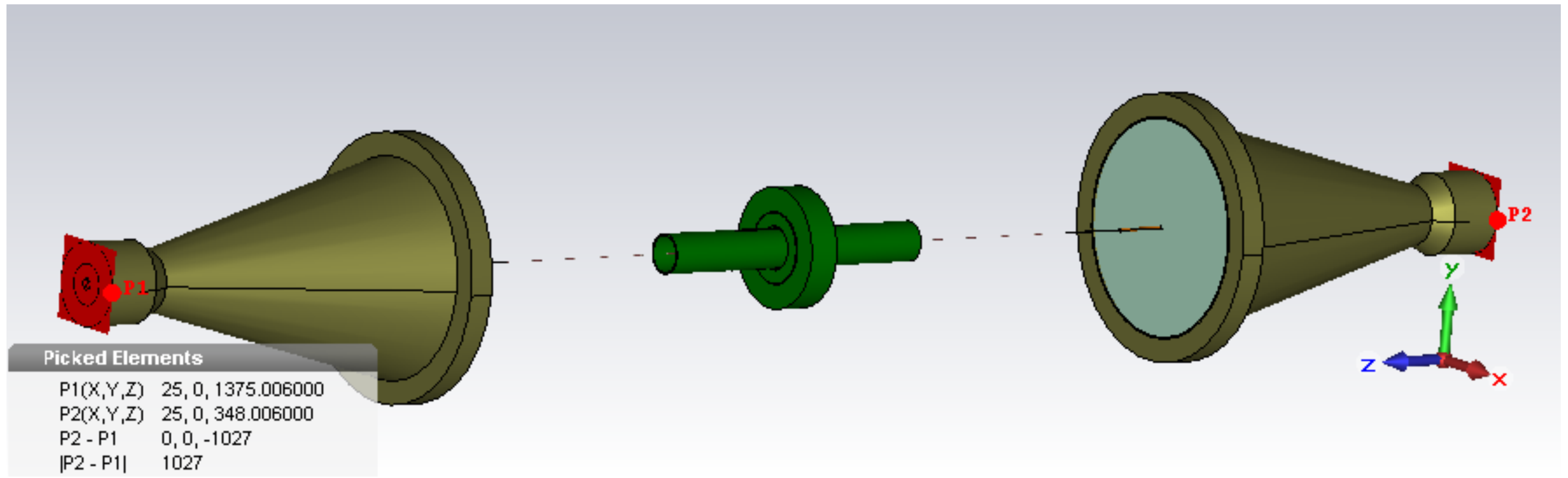
Benchmarking of the G-line Method from Simulations

- Since the application of the G-line to impedance measurement is new, we would like to see in simulation if we can get the same S_{21} as we want.
- We first benchmarked the G-line setup with well-known results of cylindrical cavity (2.54 mm wide and 24.2 mm radius).





Simulation setup without G-line using CST



Simulation setup with G-line using CST

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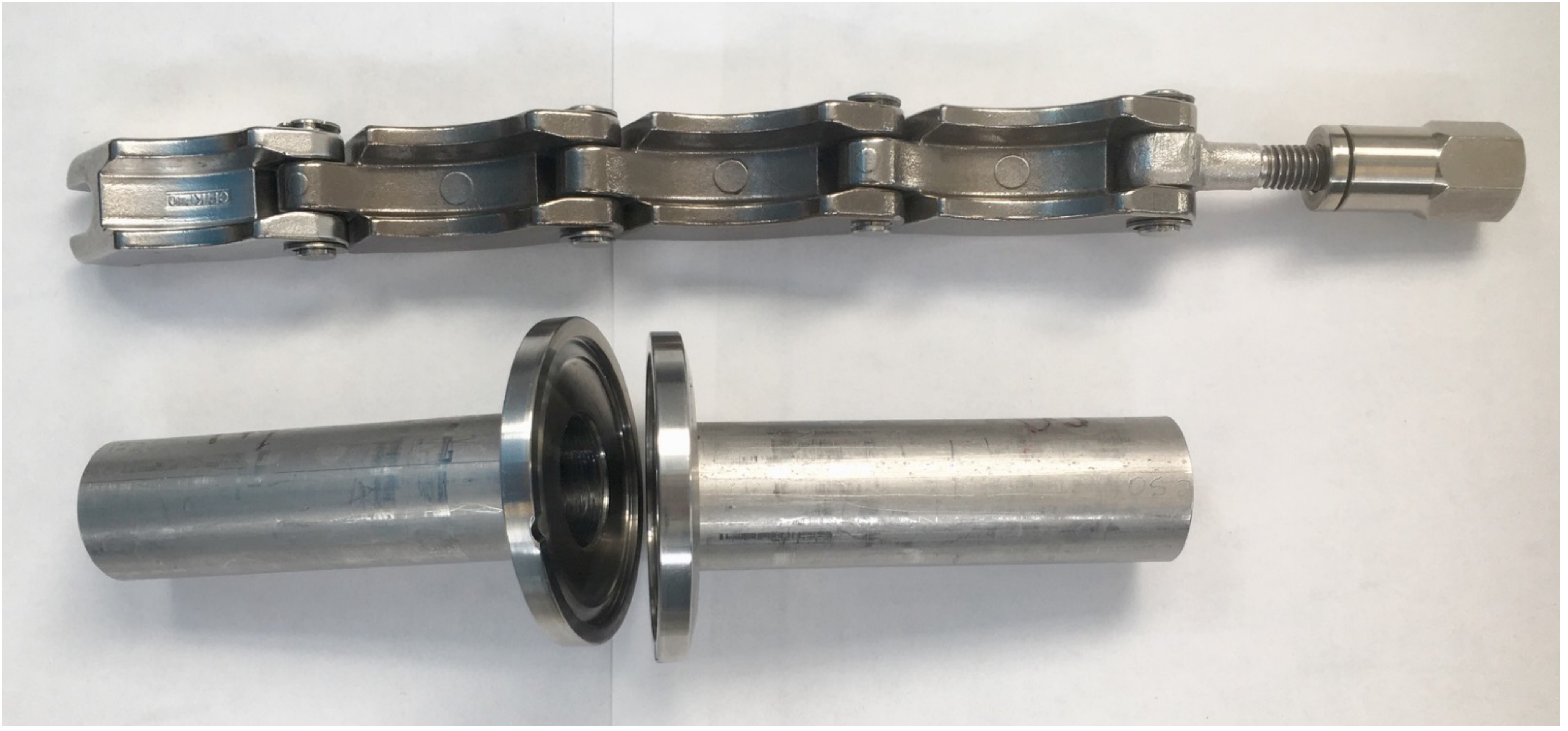
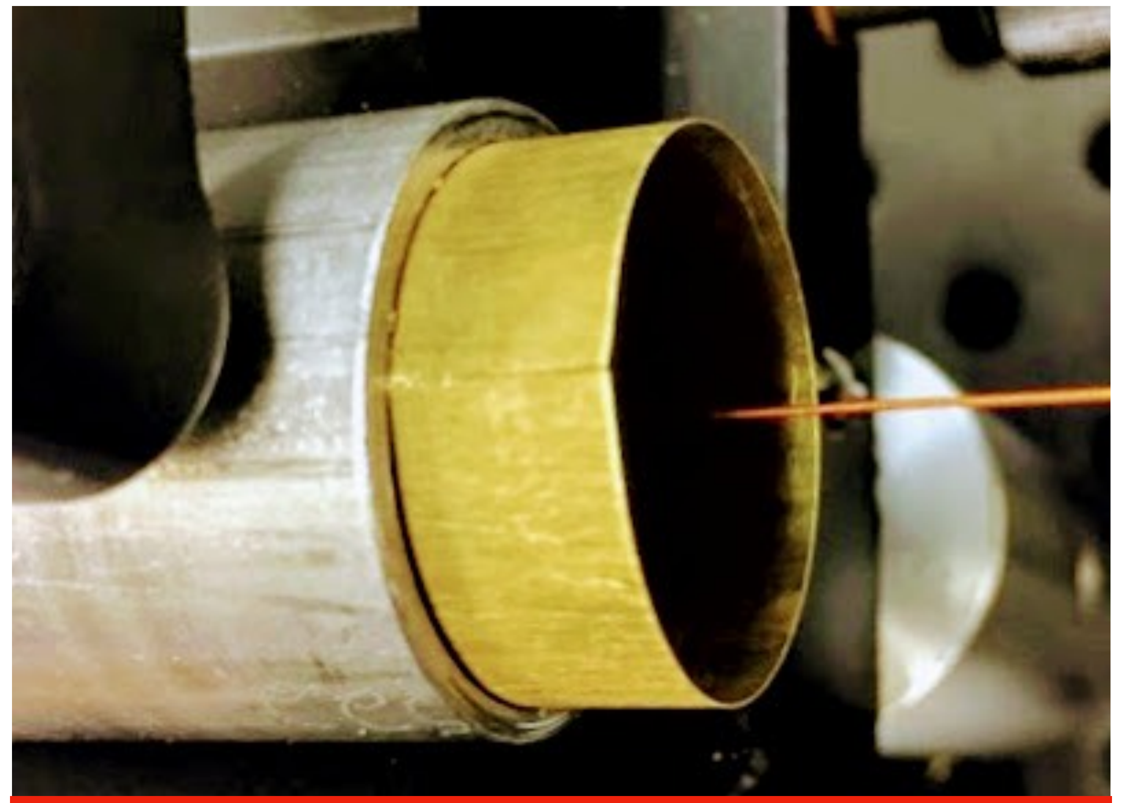
Benchmarking of the G-line Method from Measurements

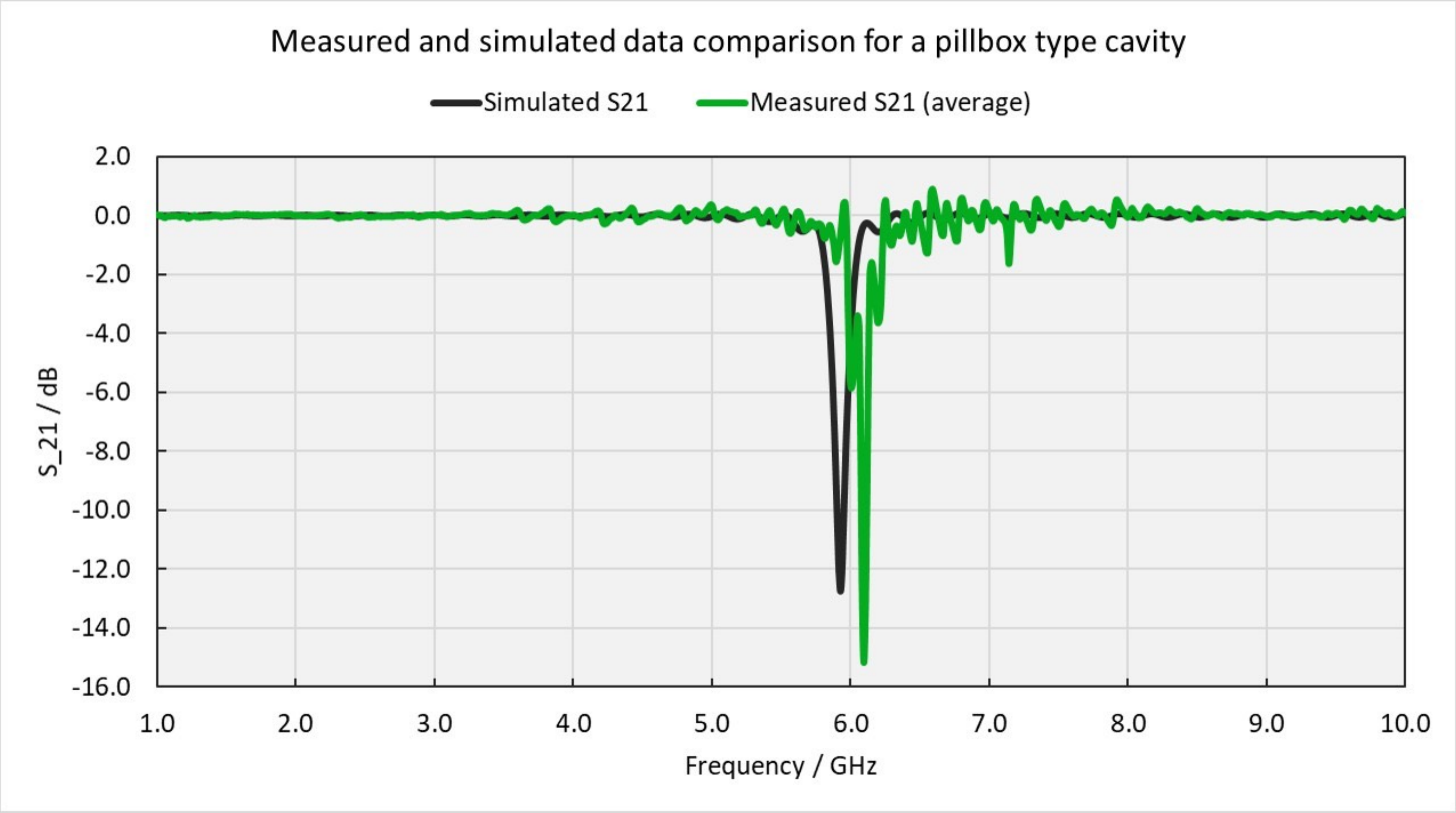
- We formed the same cylindrical cavity (2.54 mm wide and 24.2 mm radius) for experiment by joining two flanges together.
- Wrapped a copper tape around the outer circumference of the joint surface.



Chain clamp



Partially inserted sleeve inside DUT



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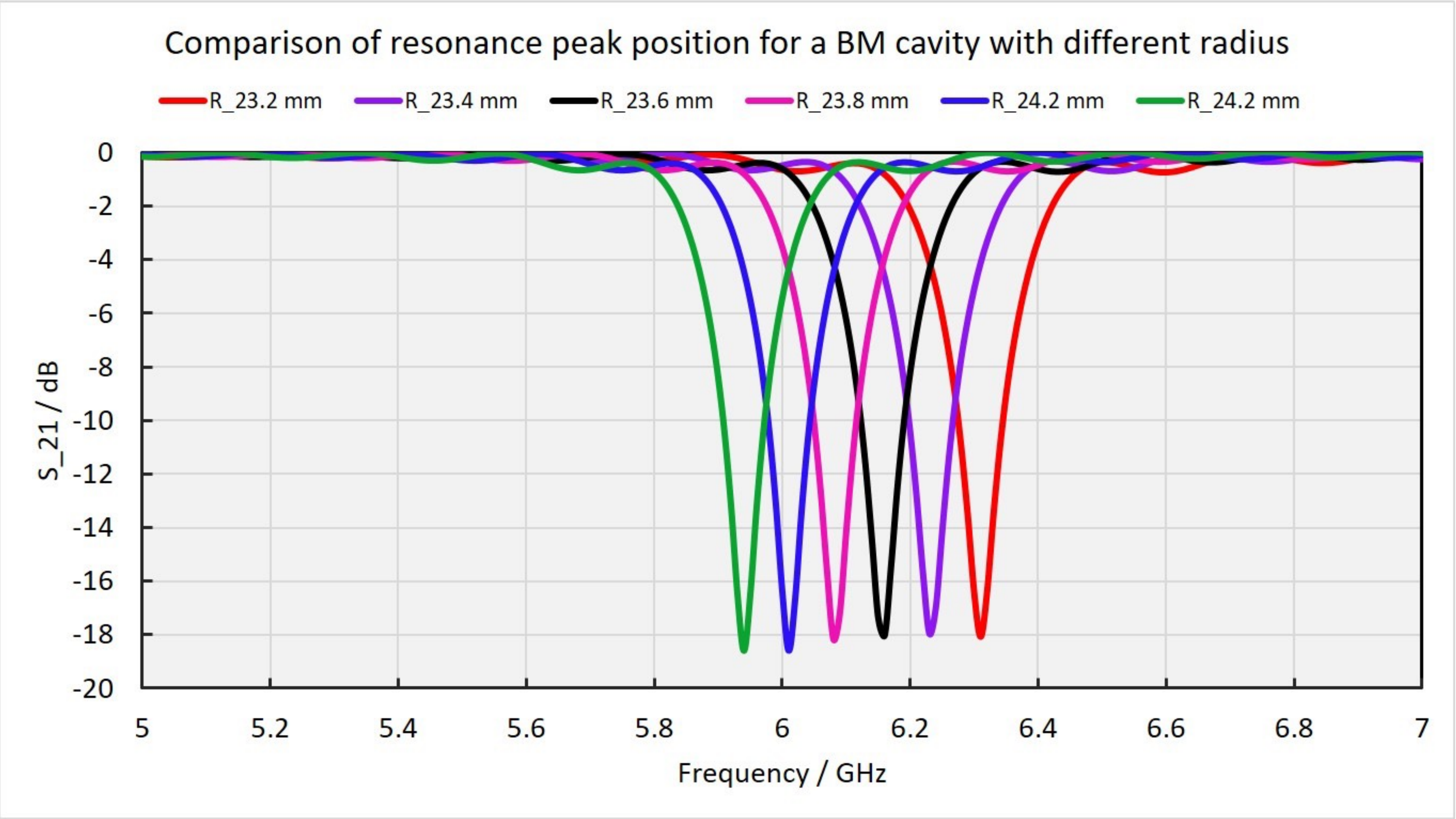
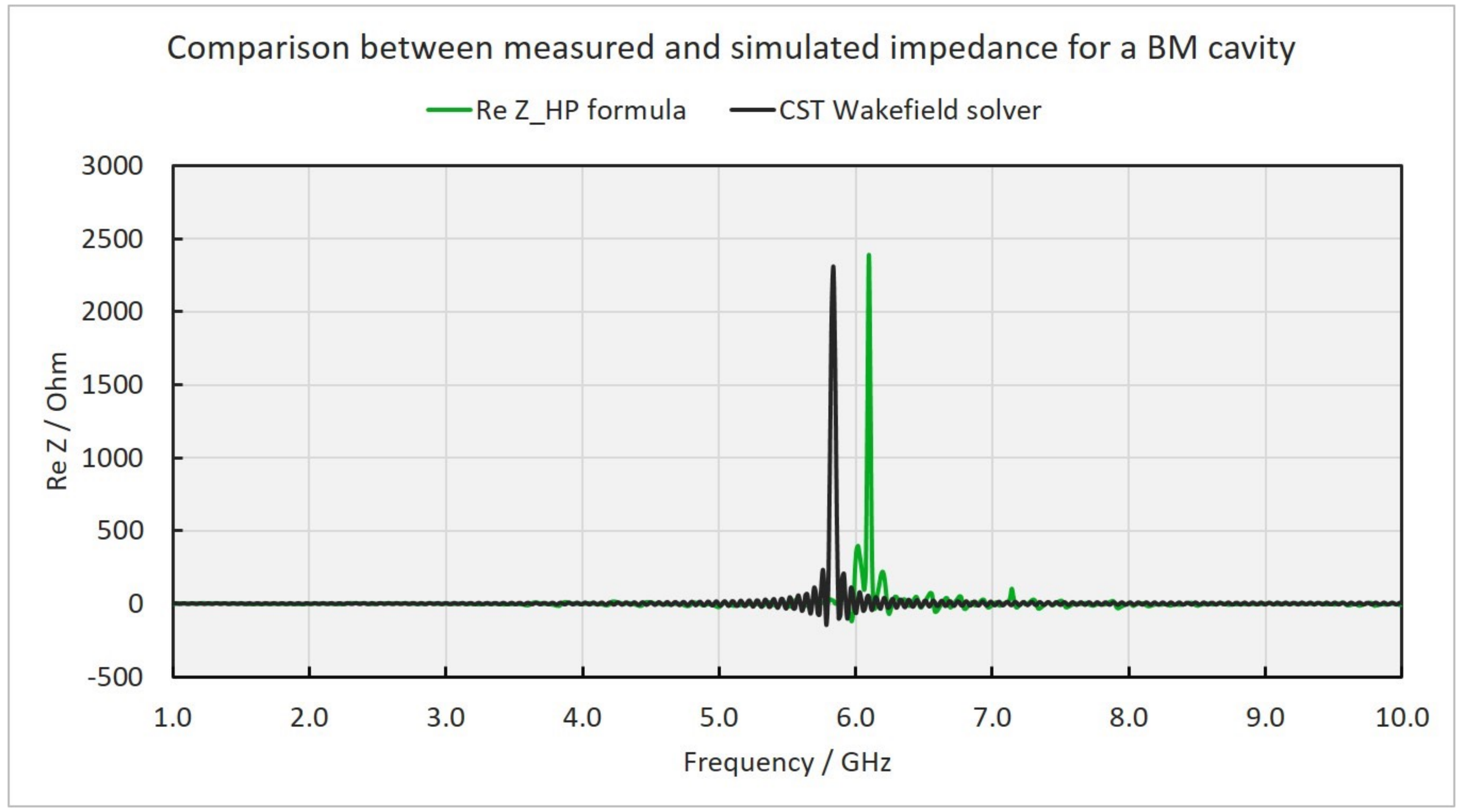
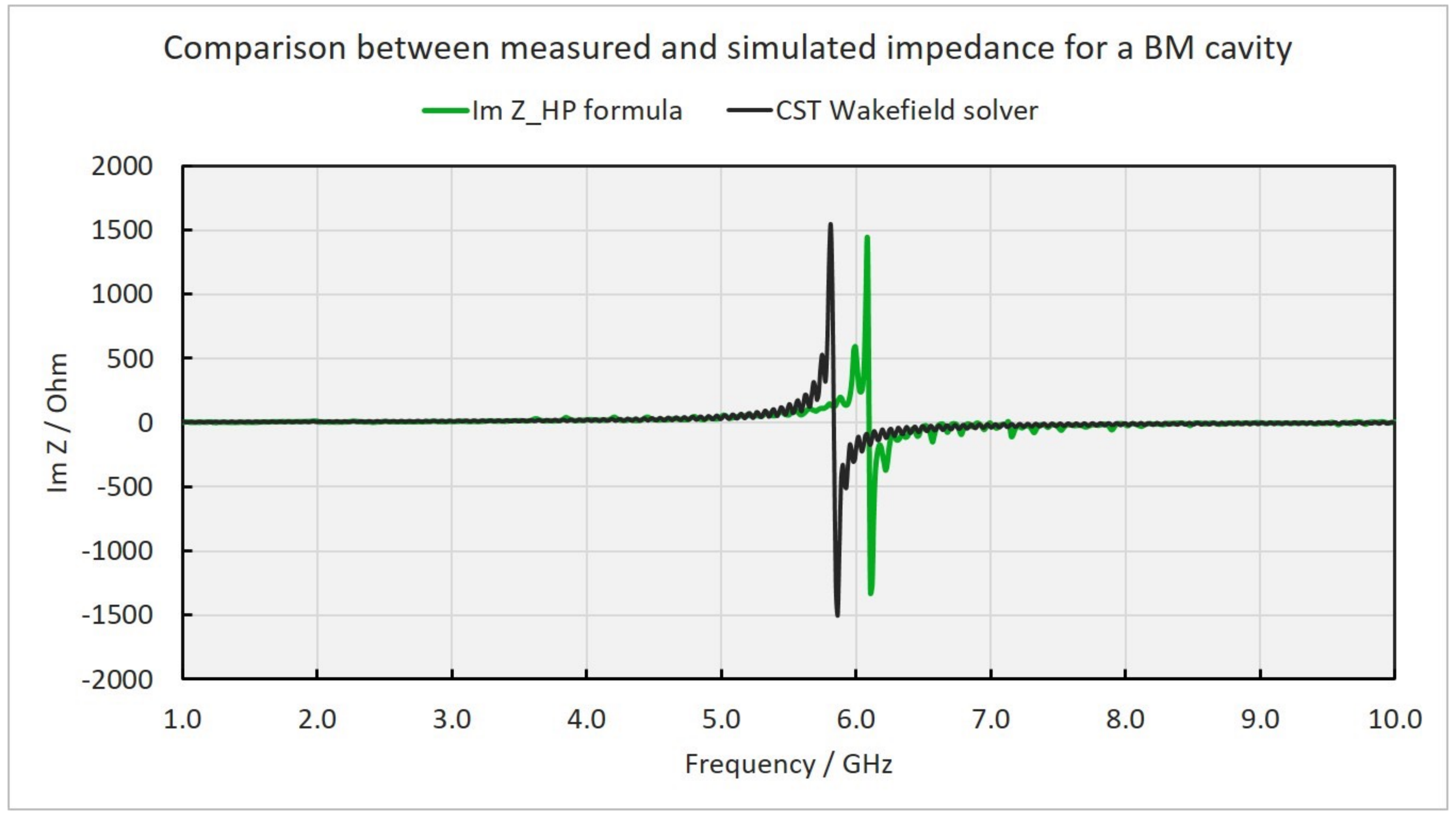
Impedance Comparison of the Benchmarking Cavity

- Looks very similar but the peak position is slightly shifted.
- Did some investigations to figure out the sensitivity of this shift in terms of geometry.
- CST simulations shows approximately 0.4 mm difference in the radial size of the cavity.







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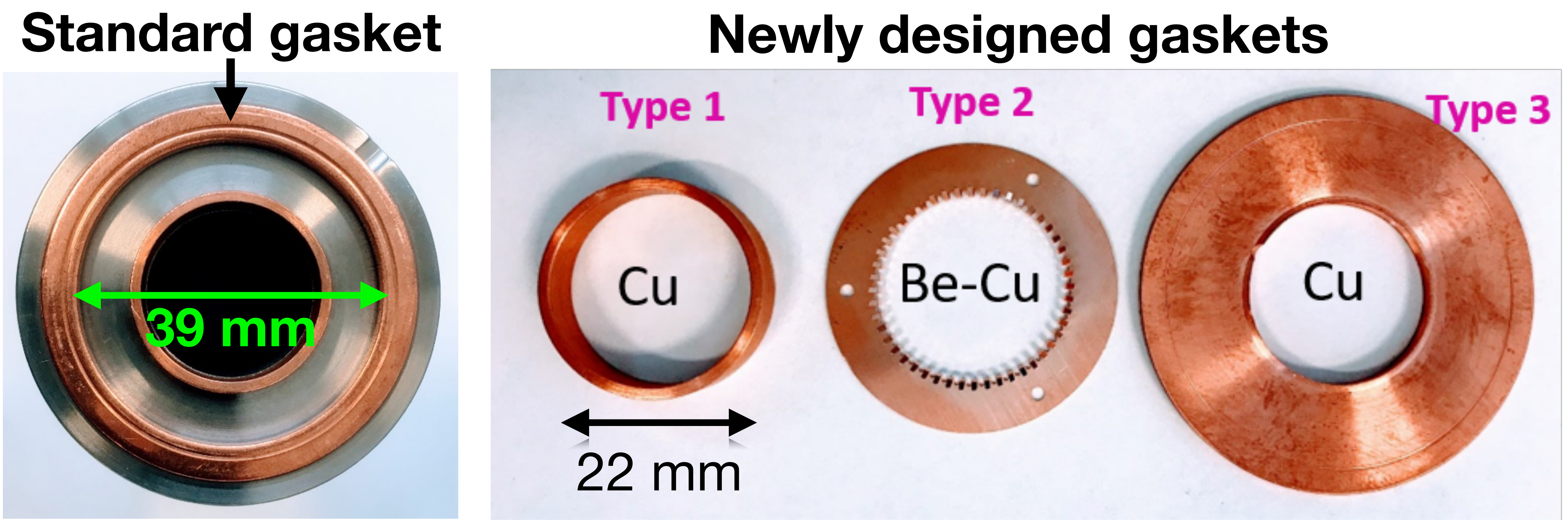
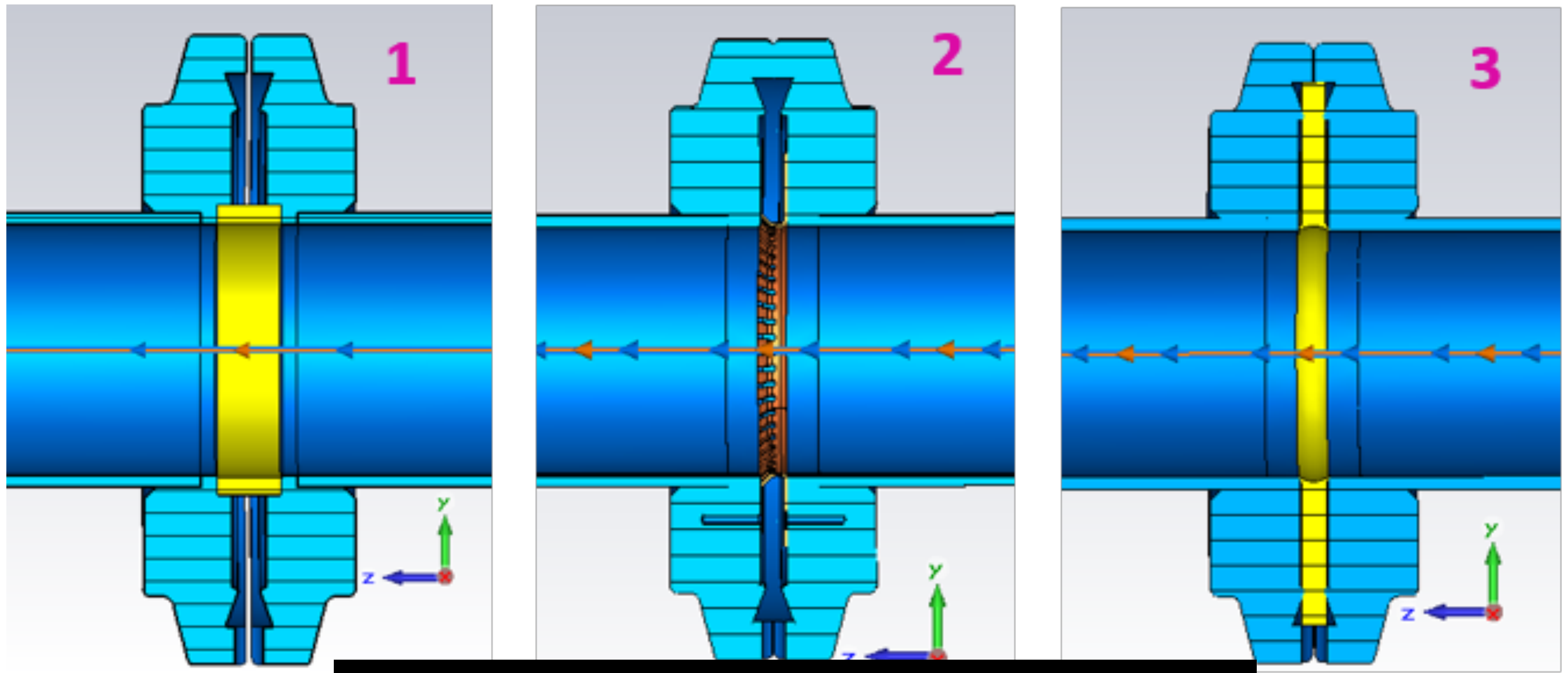
M. Sangroula and et.al,, in Proc. IPAC'18 Vancouver, Canada THPAK005

Measurement of Other Components using the G-line

Gaskets for the QCF Flange

- The standard vacuum gasket for the QCF flange introduces a large cavity structure.
- Use of standard gaskets lower the microwave instability threshold significantly as we require thousands of them in the APS-U, and hence can't be used.
- We must design a new RF-seal gasket.
- Measurement to test the performance of newly designed flange gasket is necessary.
- The first two designs require an additional standard gasket for the vacuum seal.





CAD models of flanges with gasket

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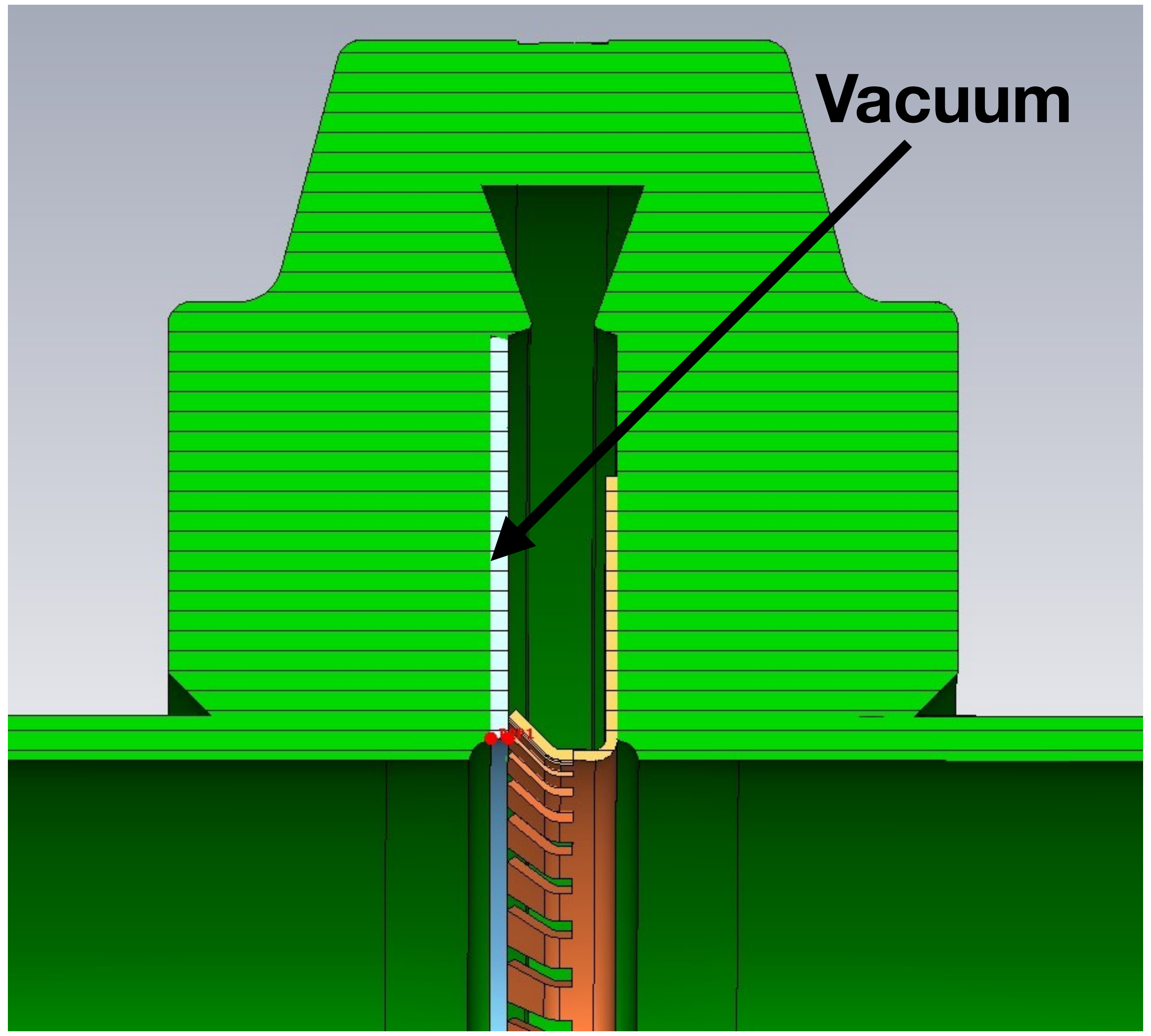
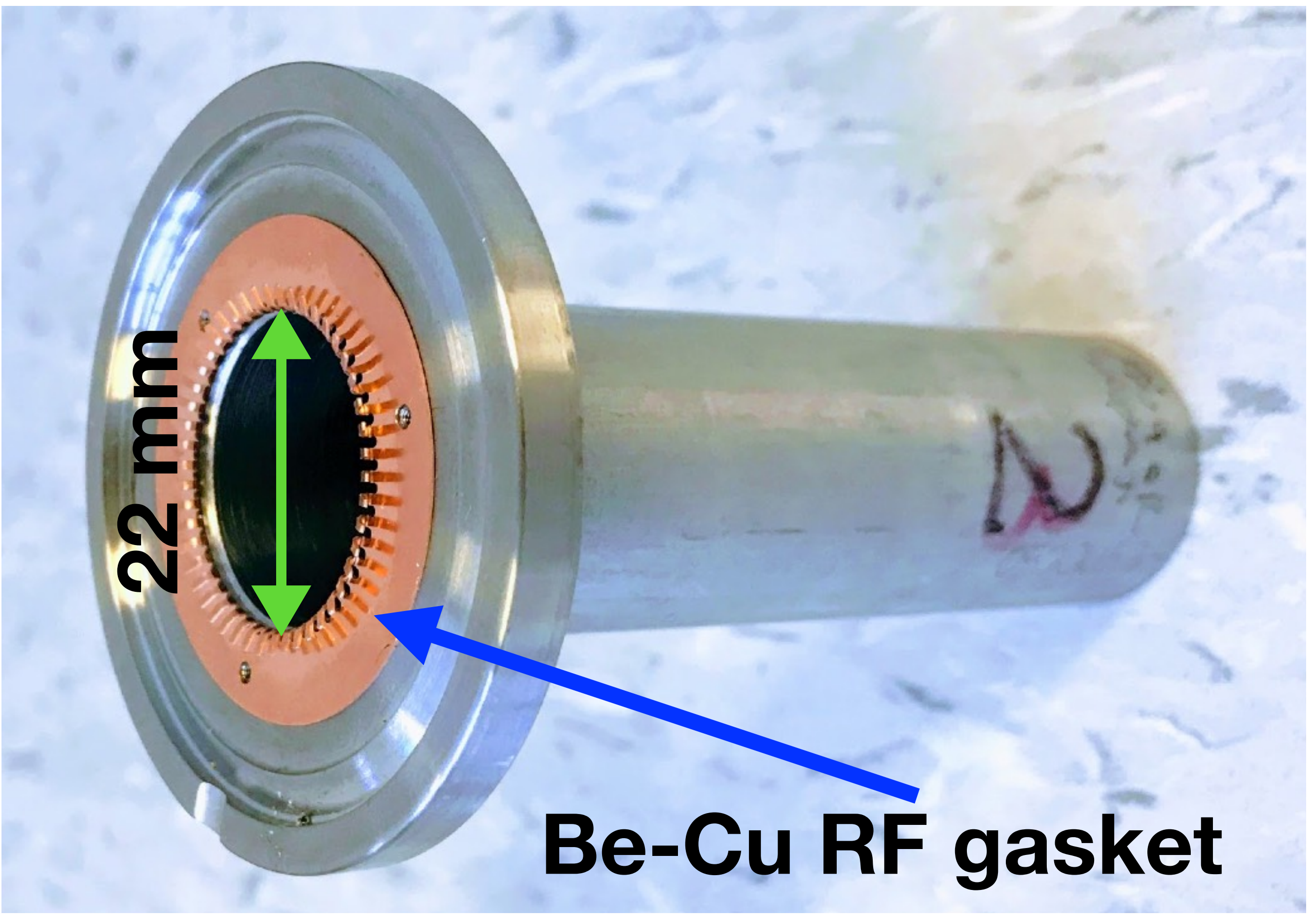
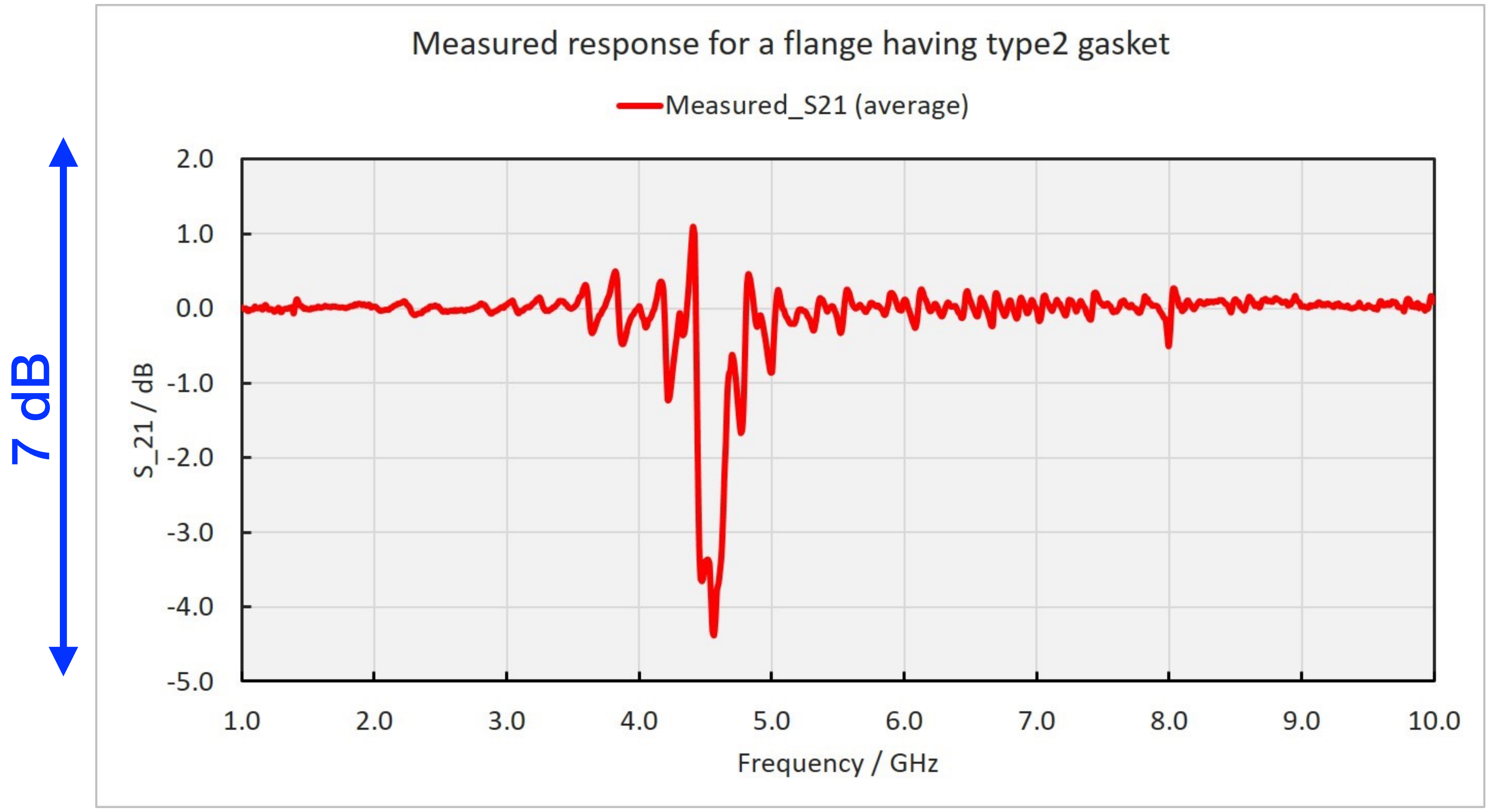
Flange with type 2 Be-Cu RF Gasket

- Surprisingly observed a resonance peak during initial measurement, which was not predicted by simulation.
- **Found an RF-gap.**







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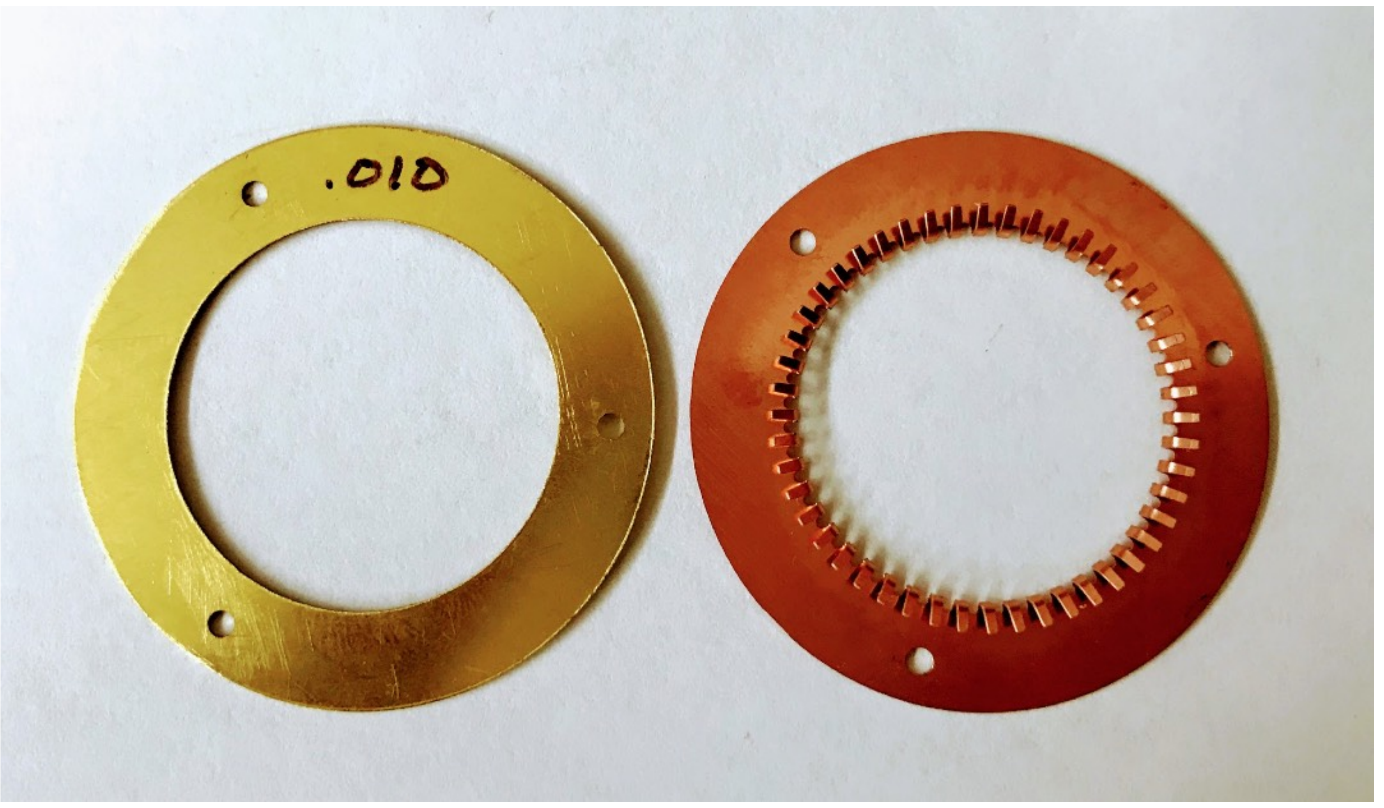
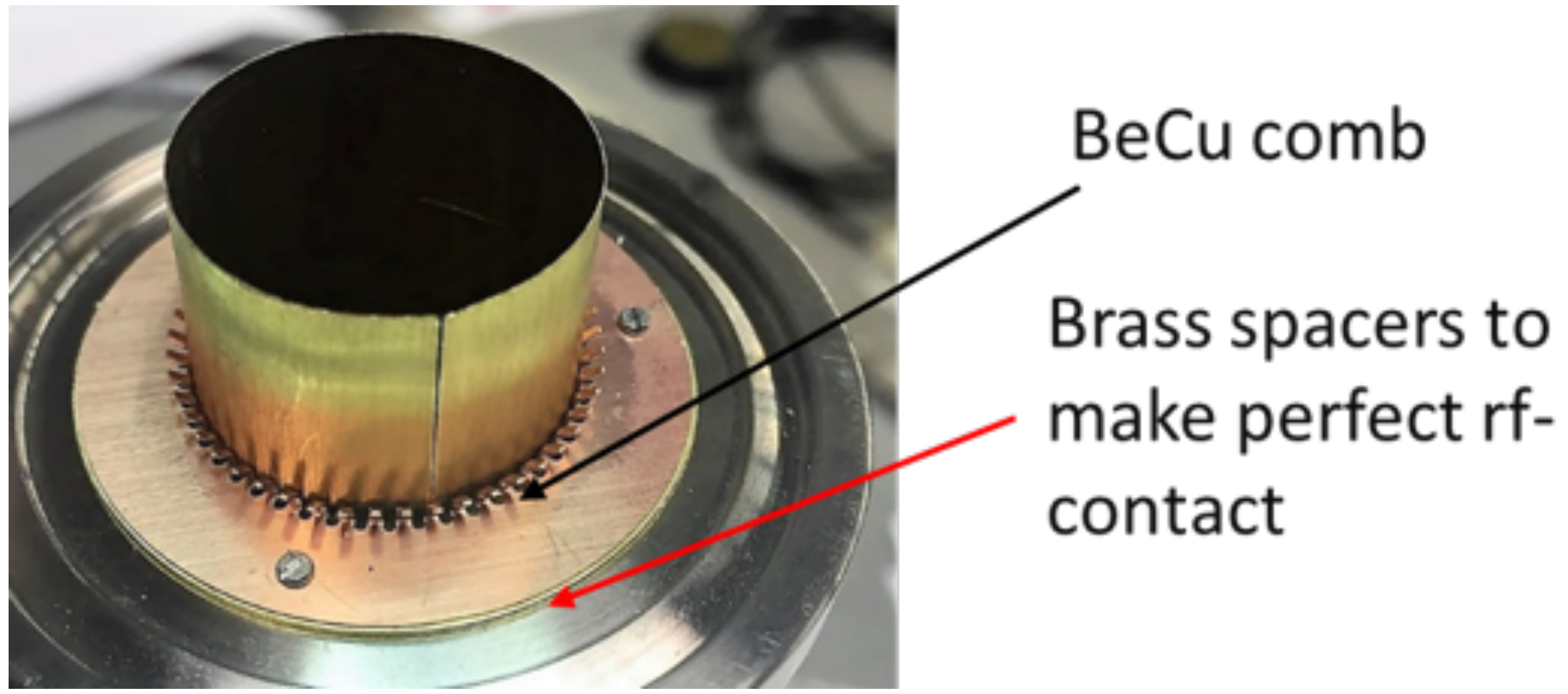
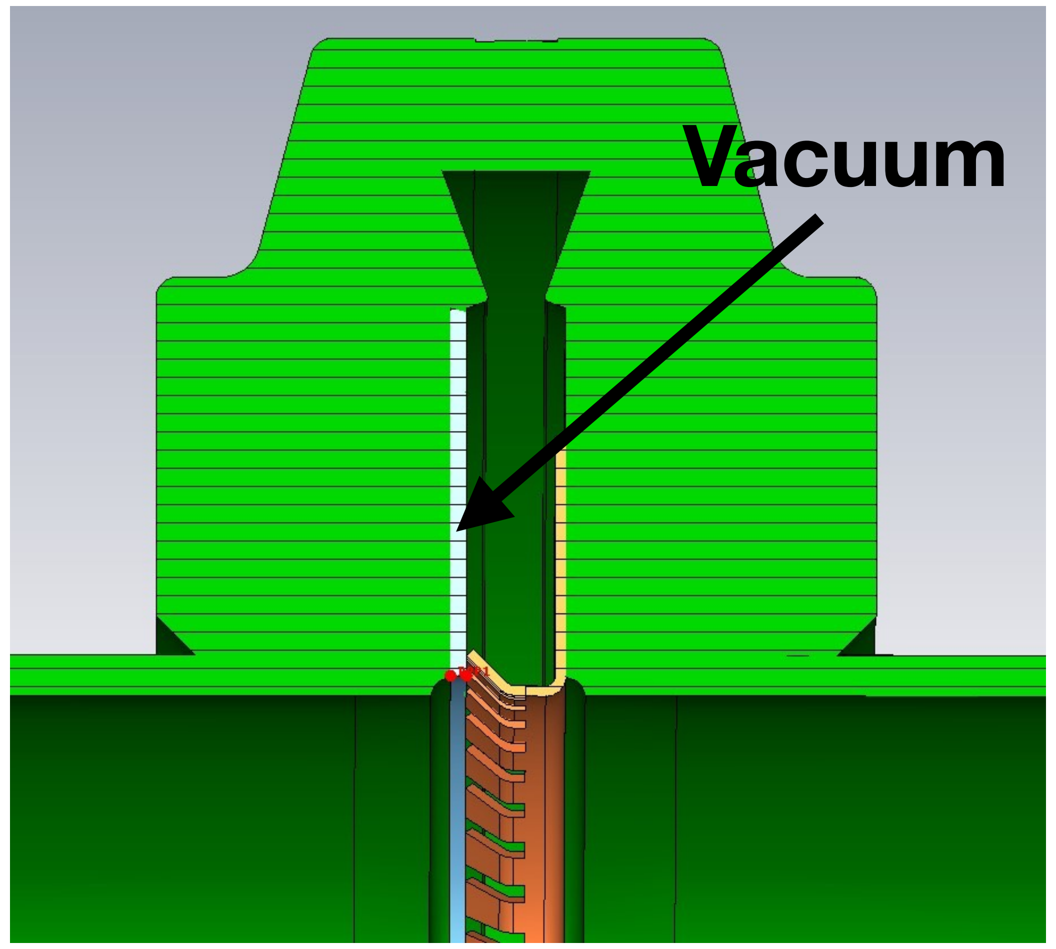
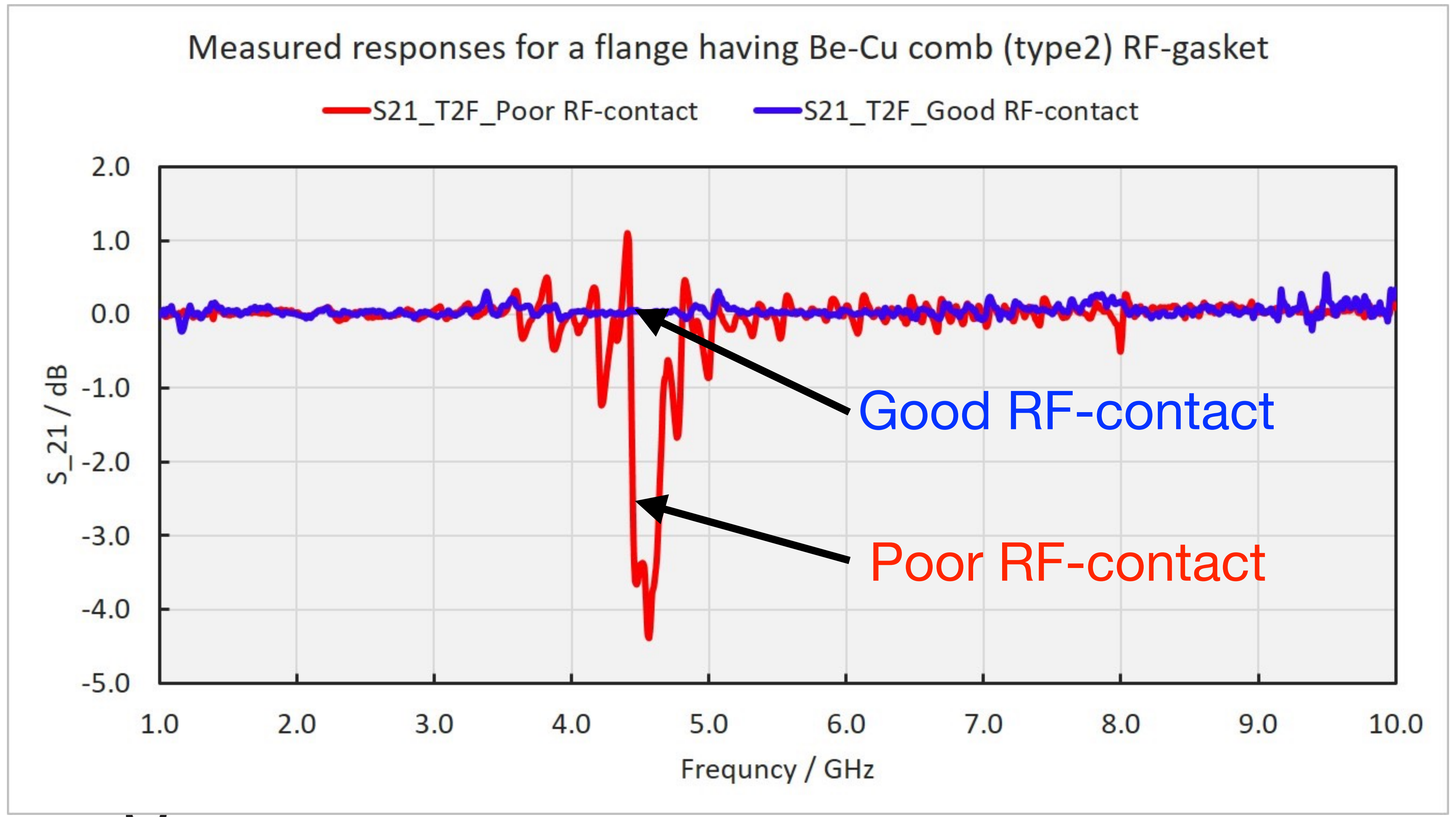
Flange with type 2 Be-Cu RF Gasket

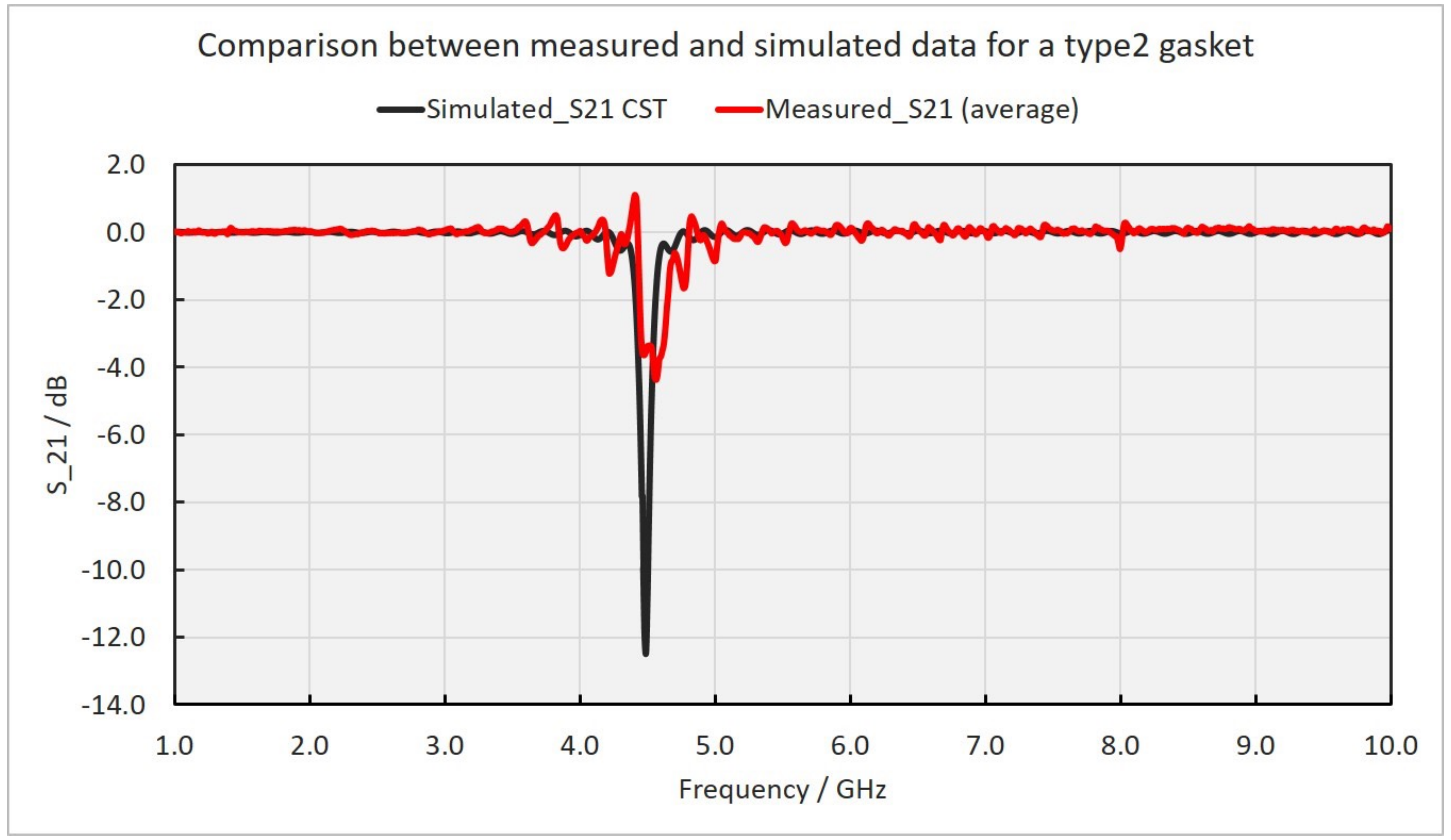
- Used brass spacers to eliminate this RF-gap.



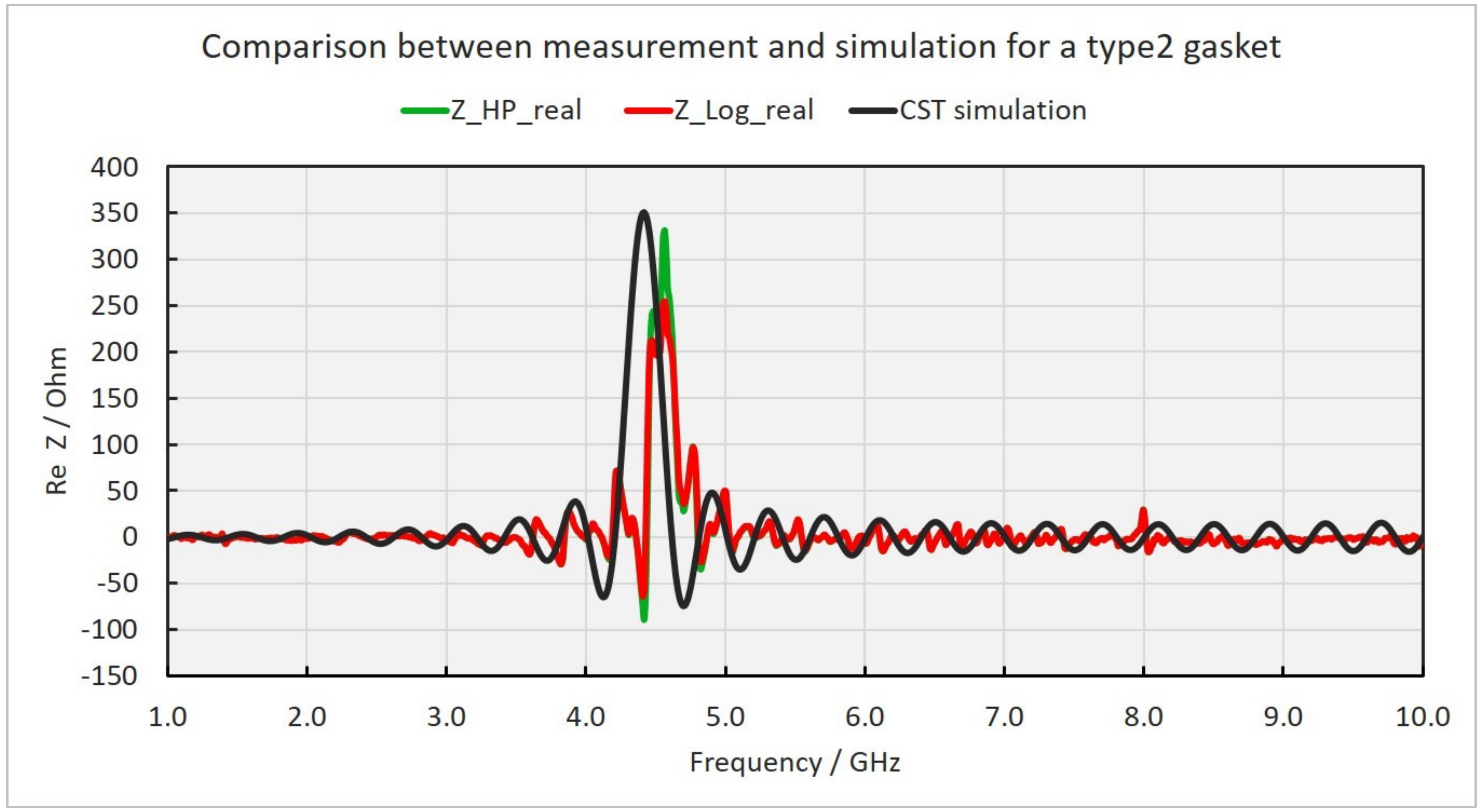




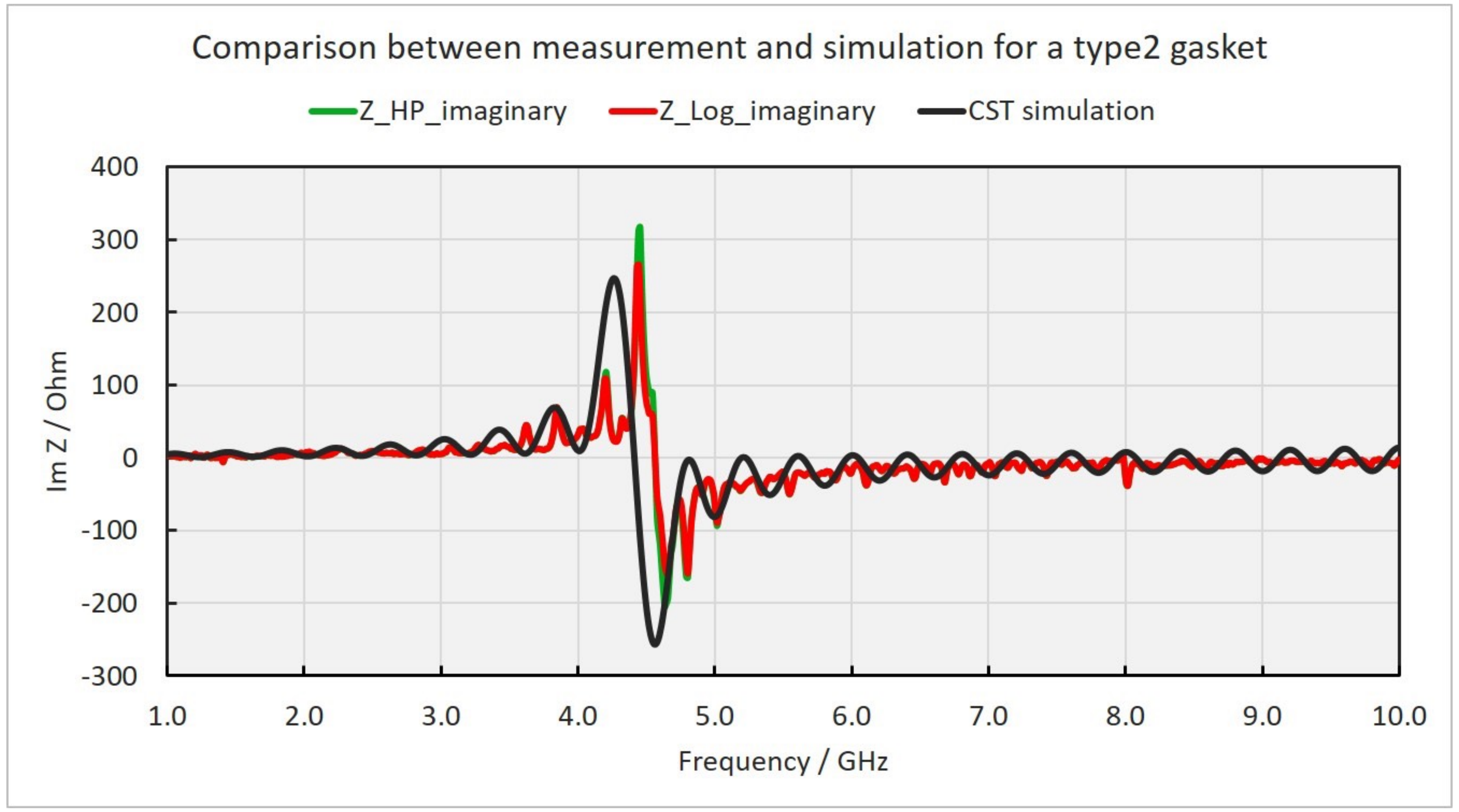




Impedance Evaluation of Flange with Be-Cu RF Gasket



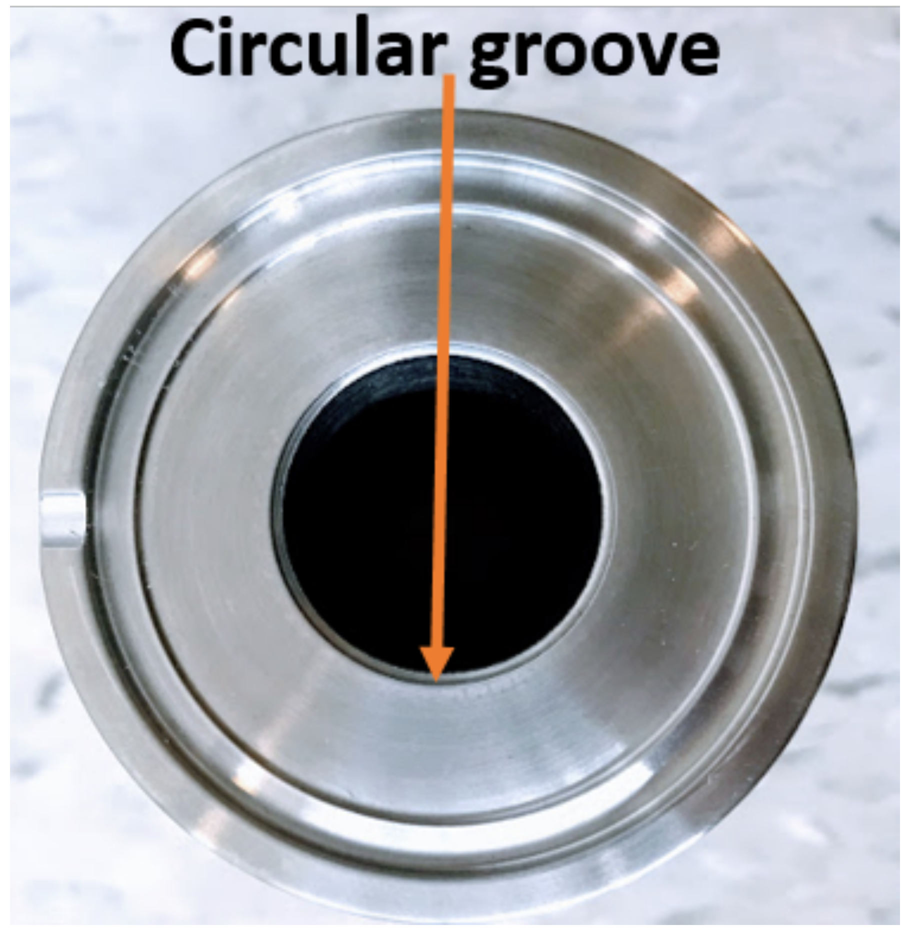
Real part of impedance

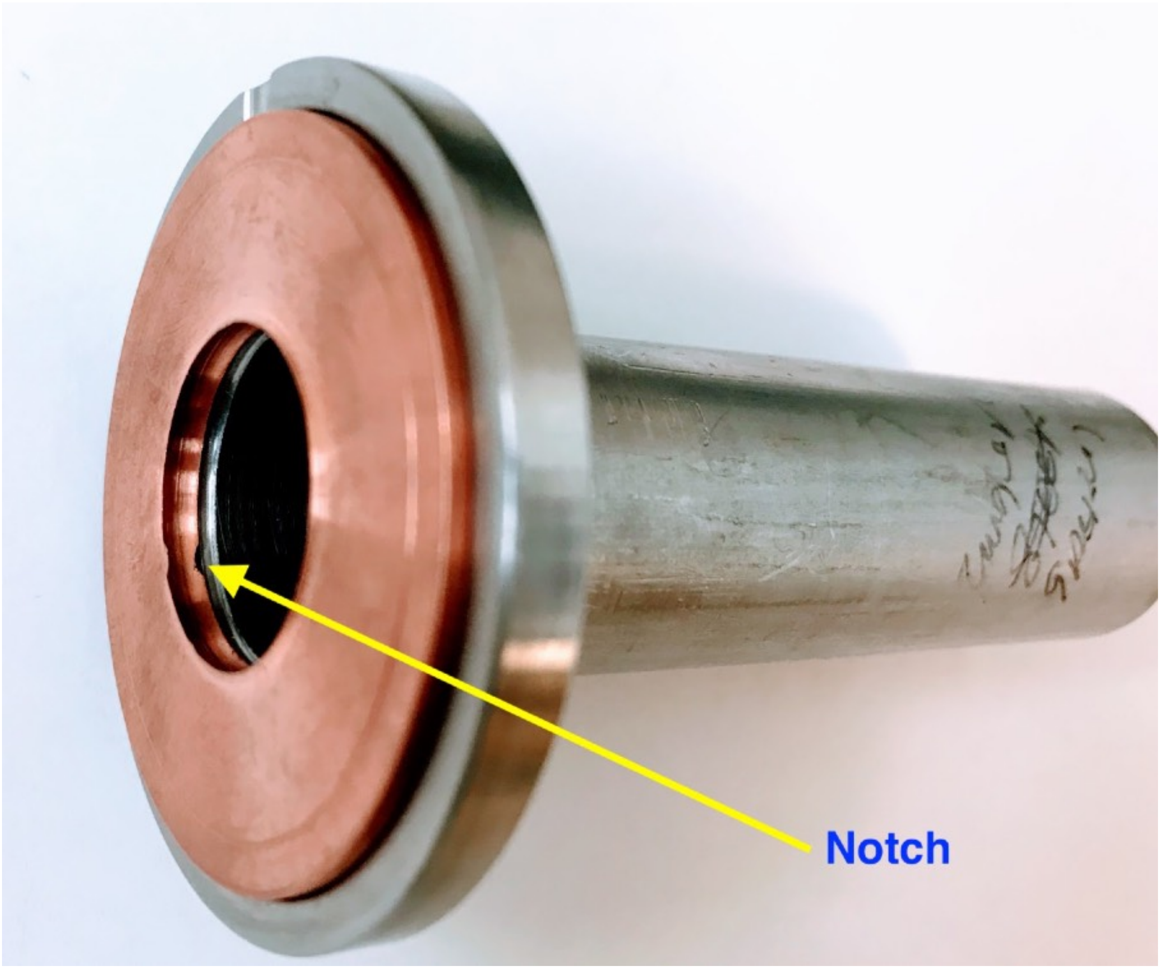


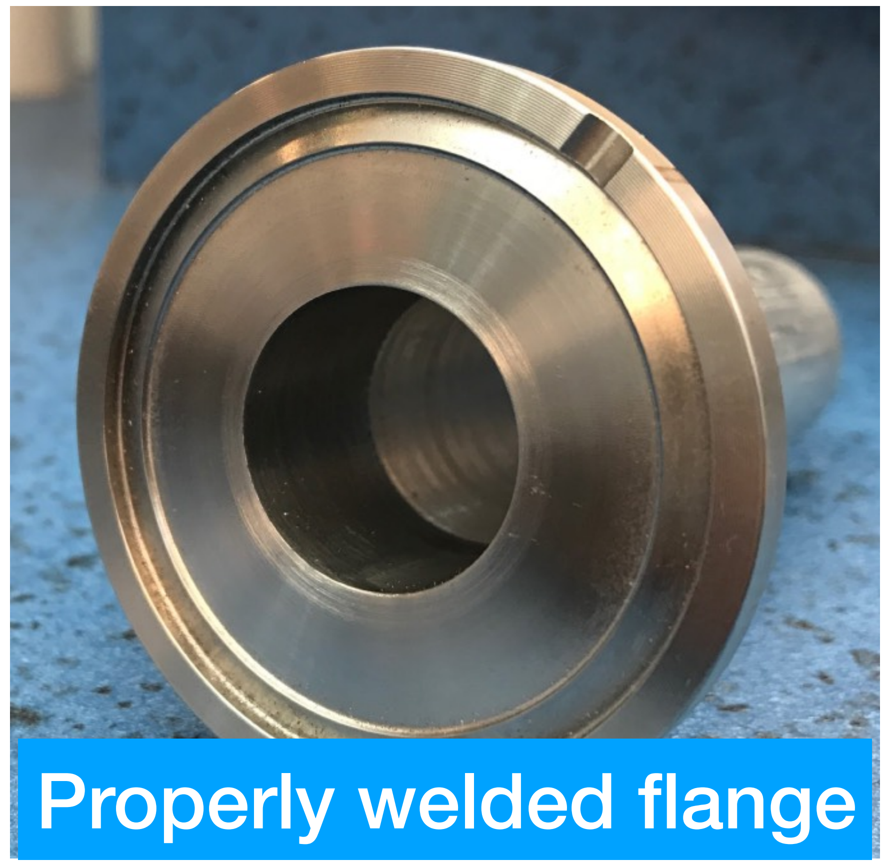
Imaginary part of impedance

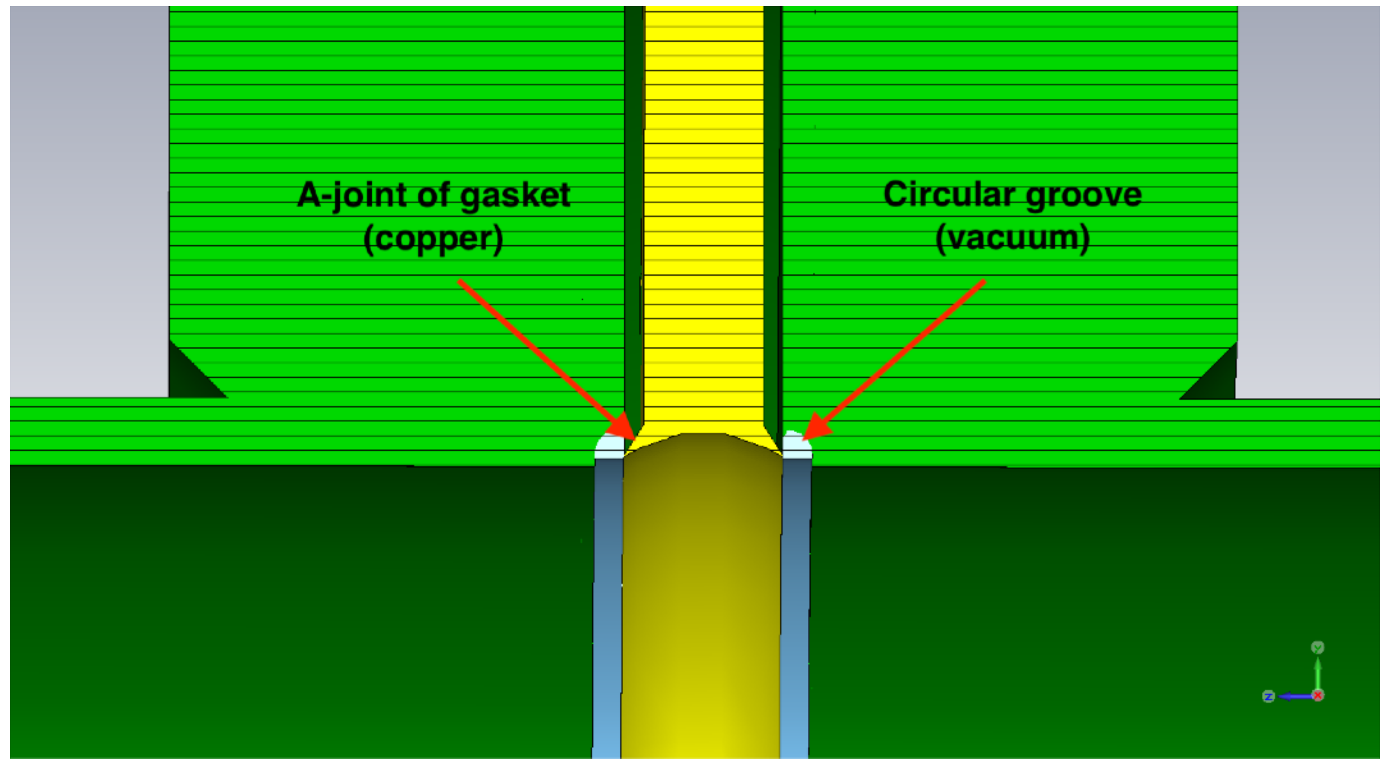
Flange with Type 3 Gasket

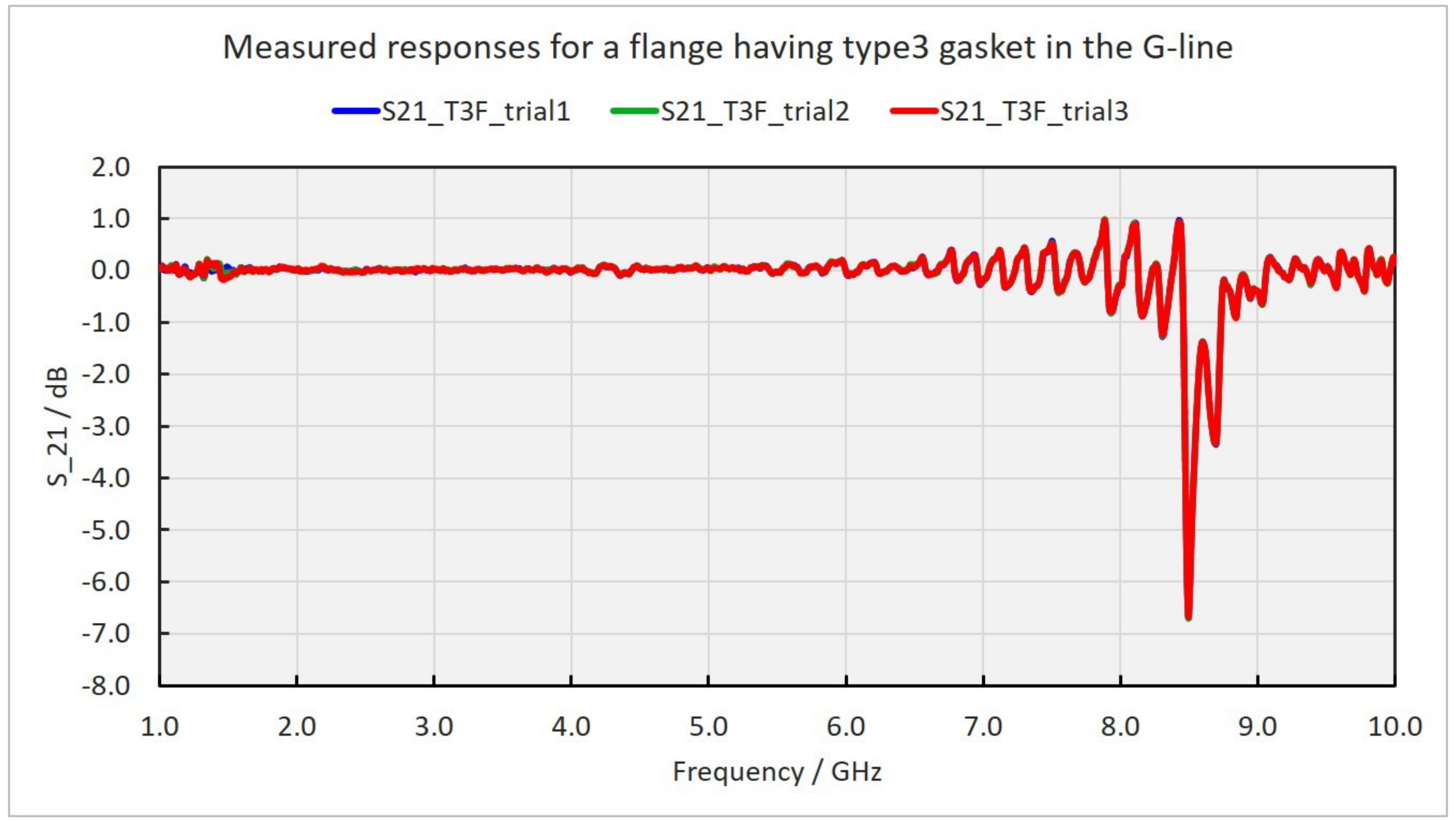
- We also observed a resonance peak, which was not predicted by simulation.

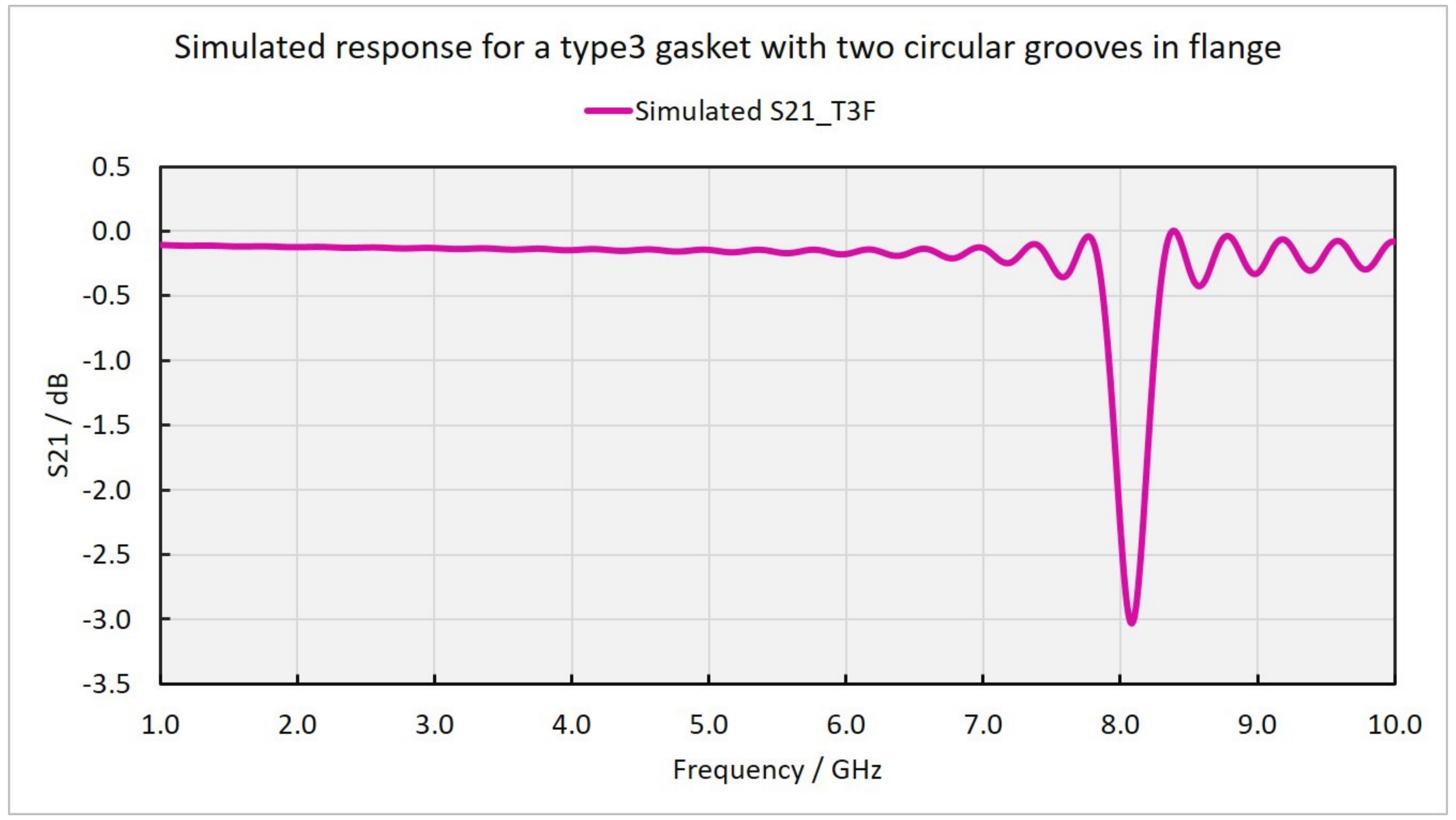












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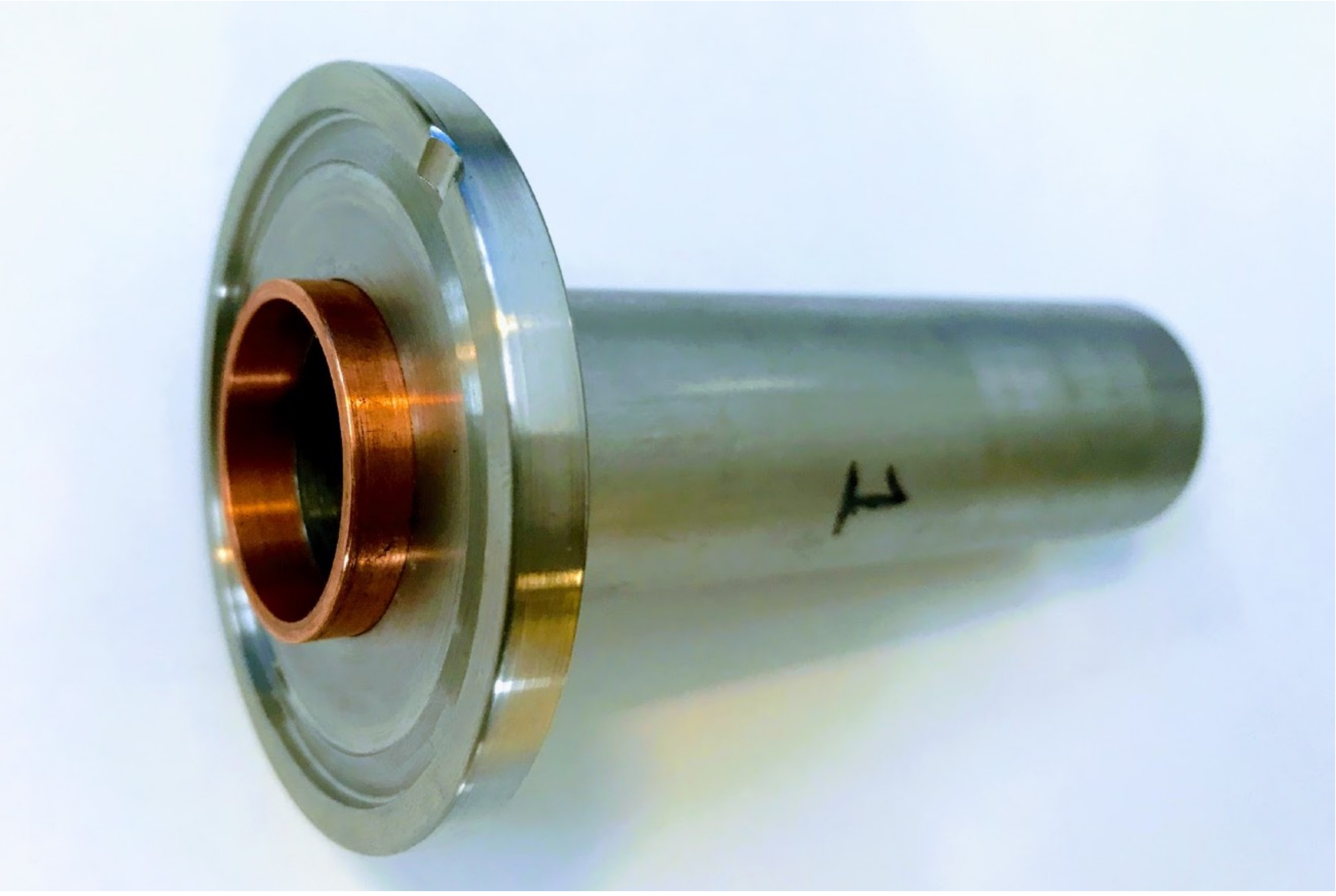
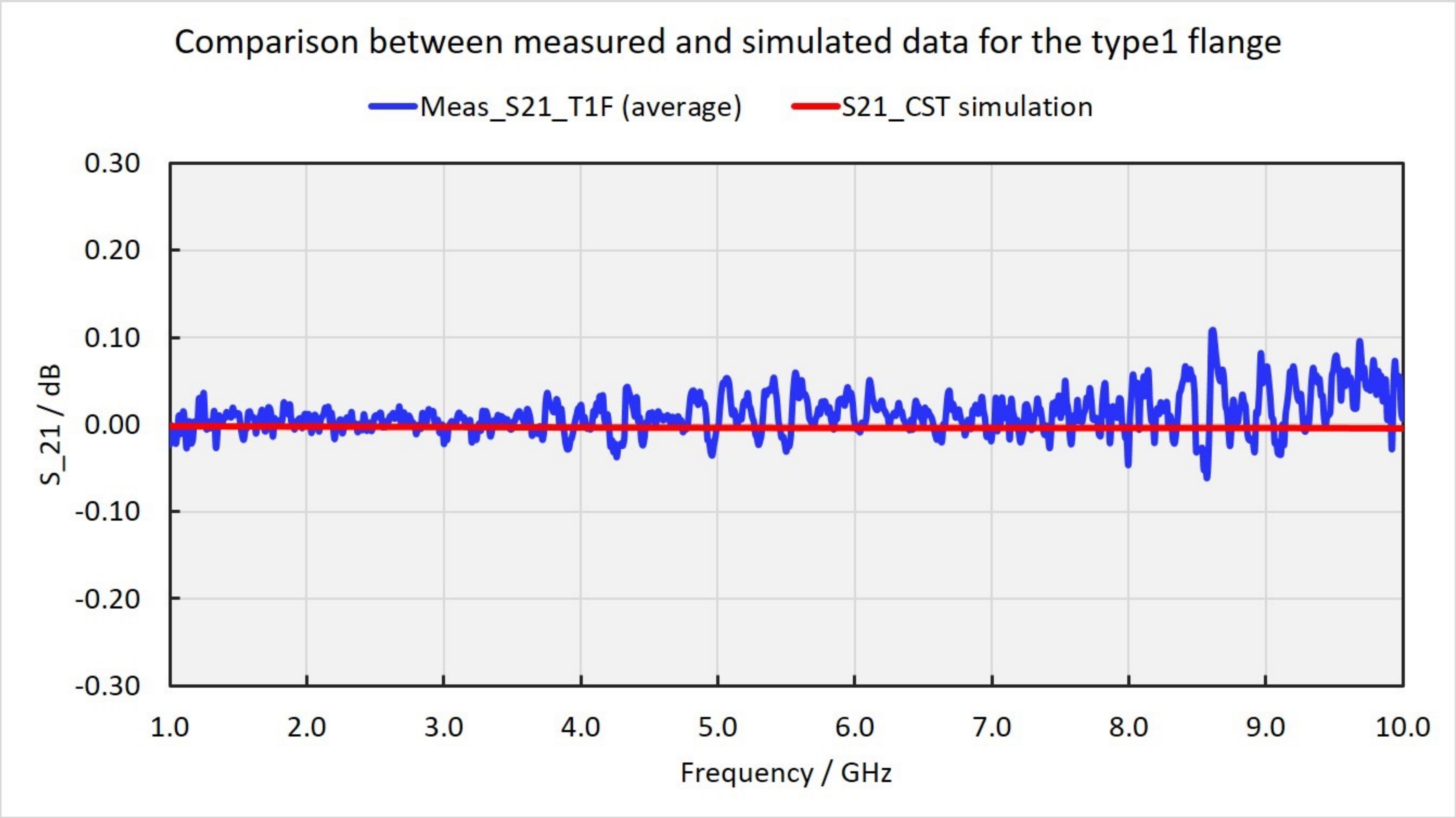
Flange with Type 1 gasket



0.6 dB



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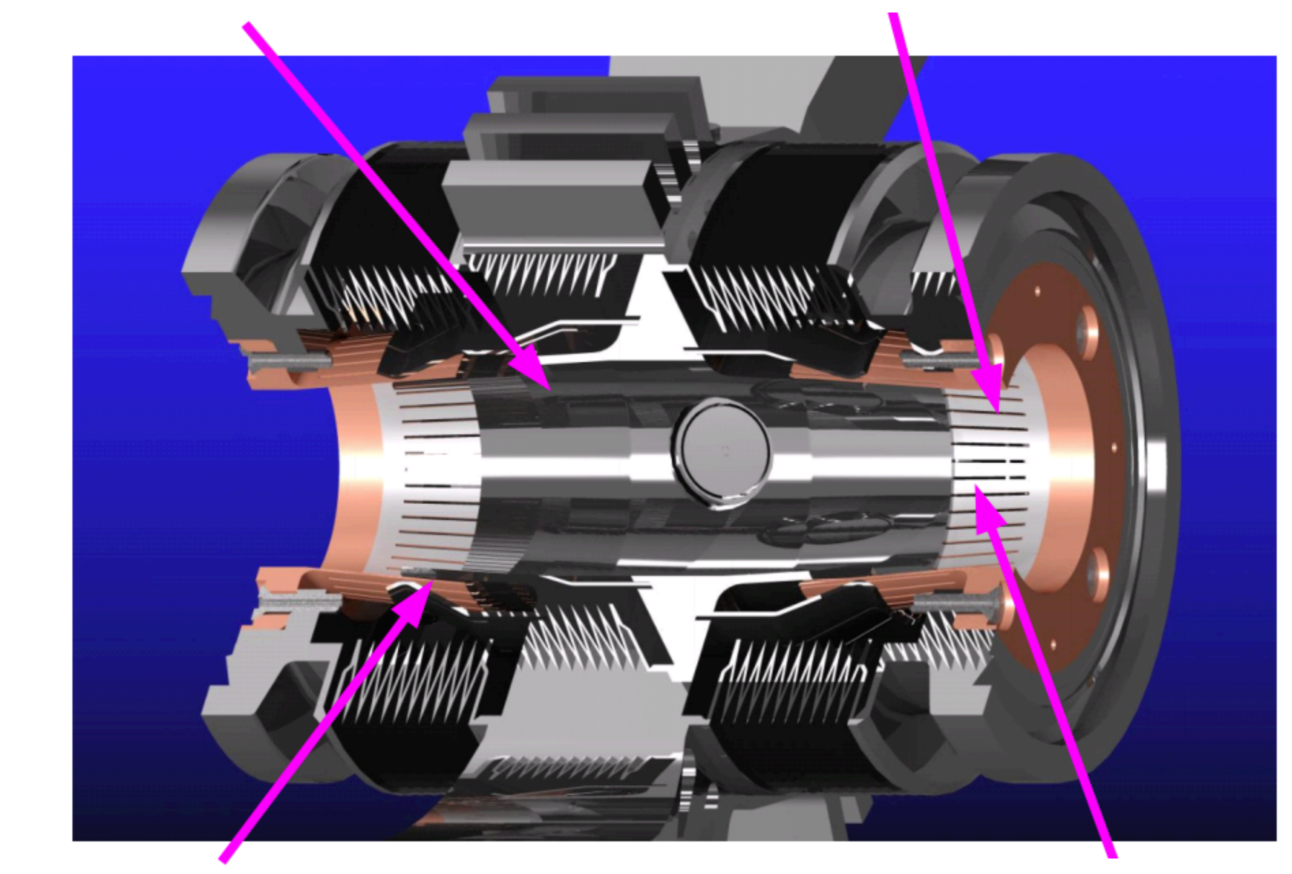
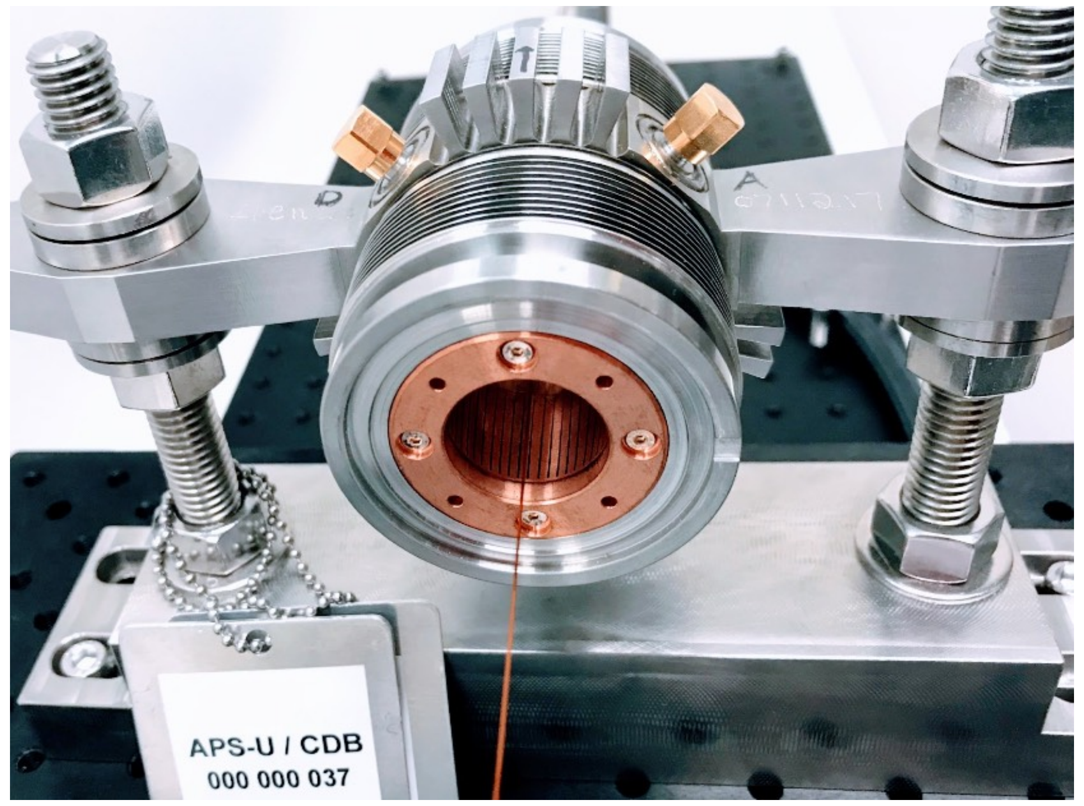
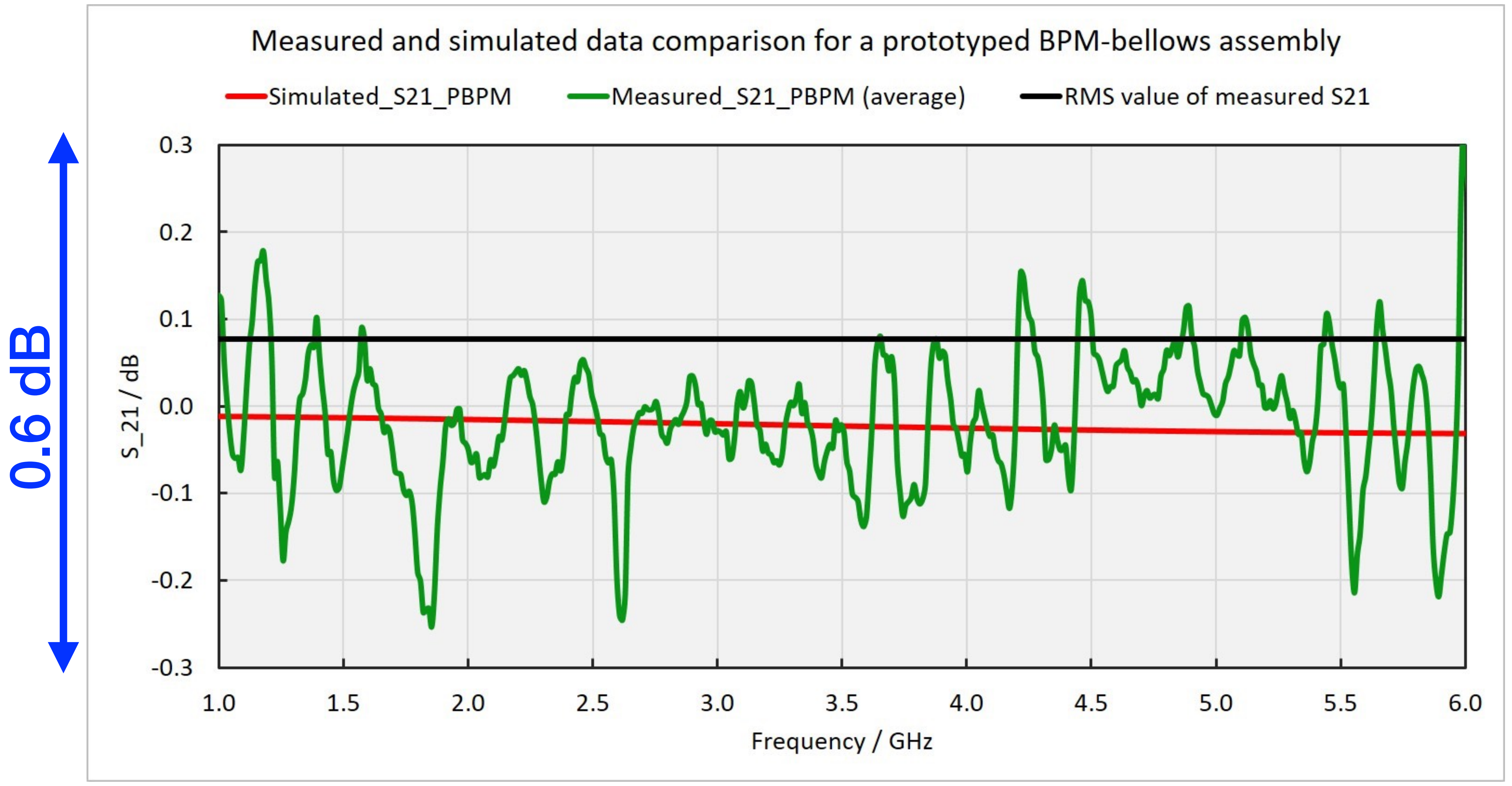
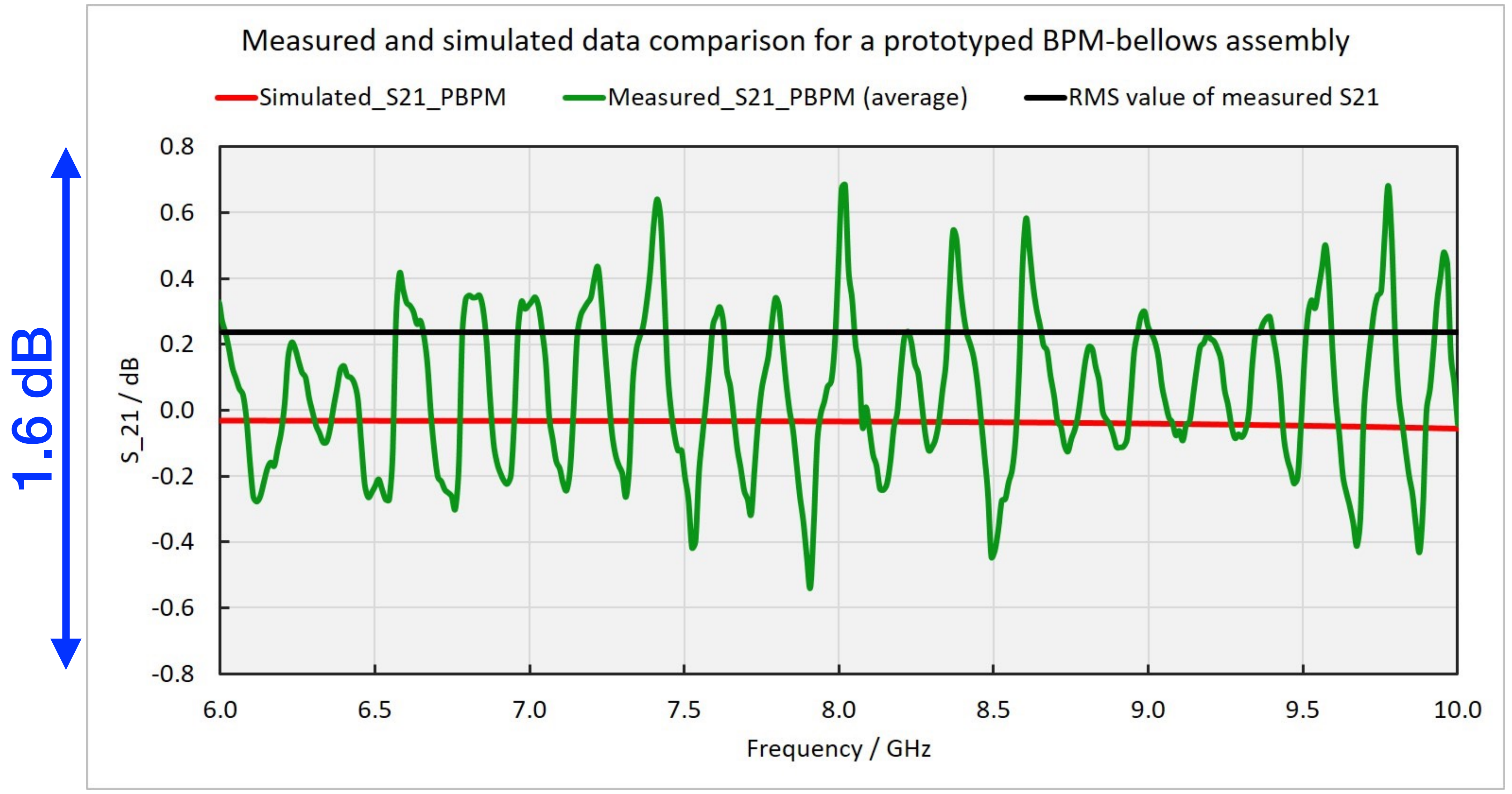
Beam Position Monitor (BPM)-bellows Assembly

- BPM is a critical diagnostic tool that provides information regarding on the beam position.
- Mechanical stability tolerances is ~ 1-micron rms/per week. Any local heating can potentially displace the buttons and overwhelm these tolerances.



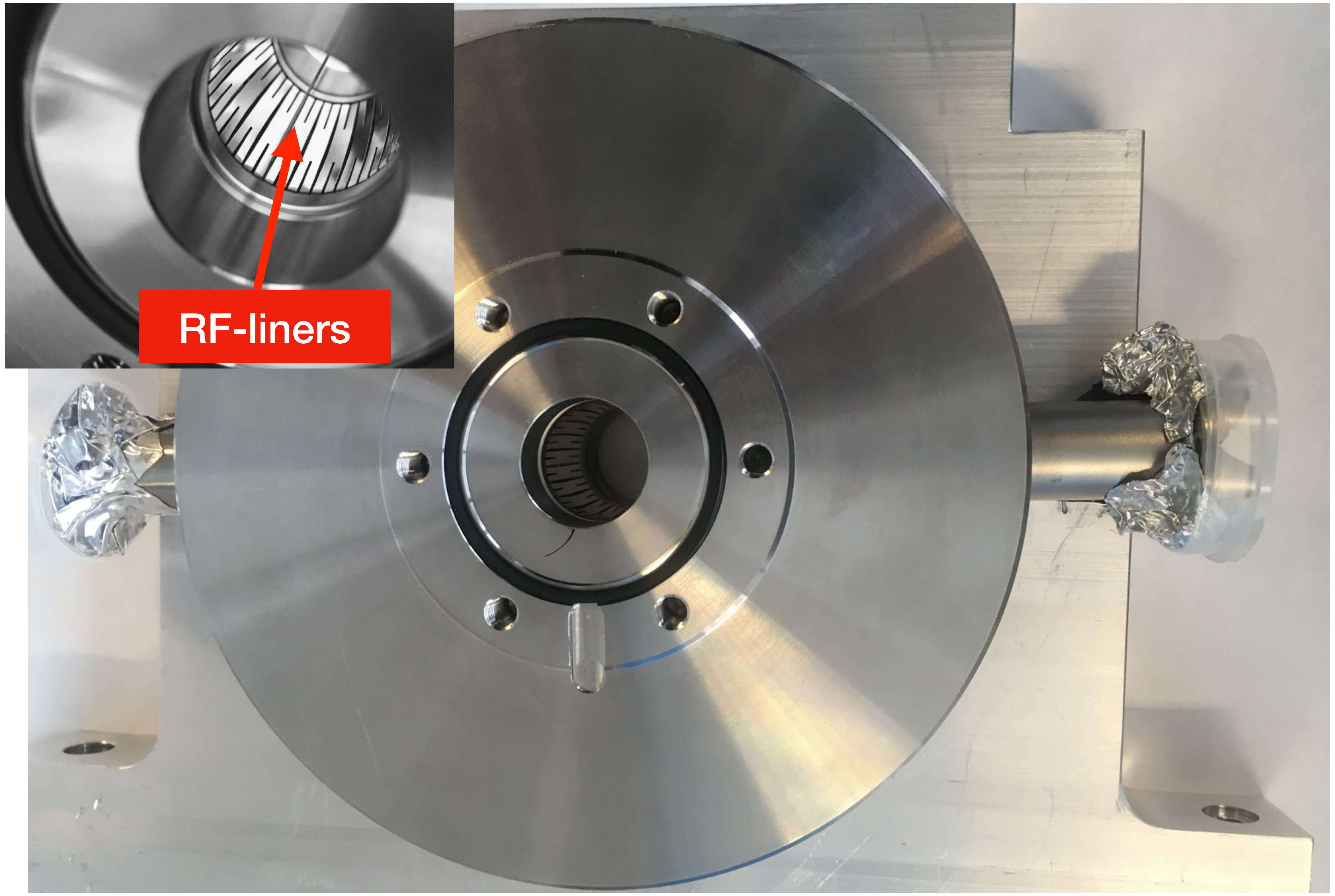


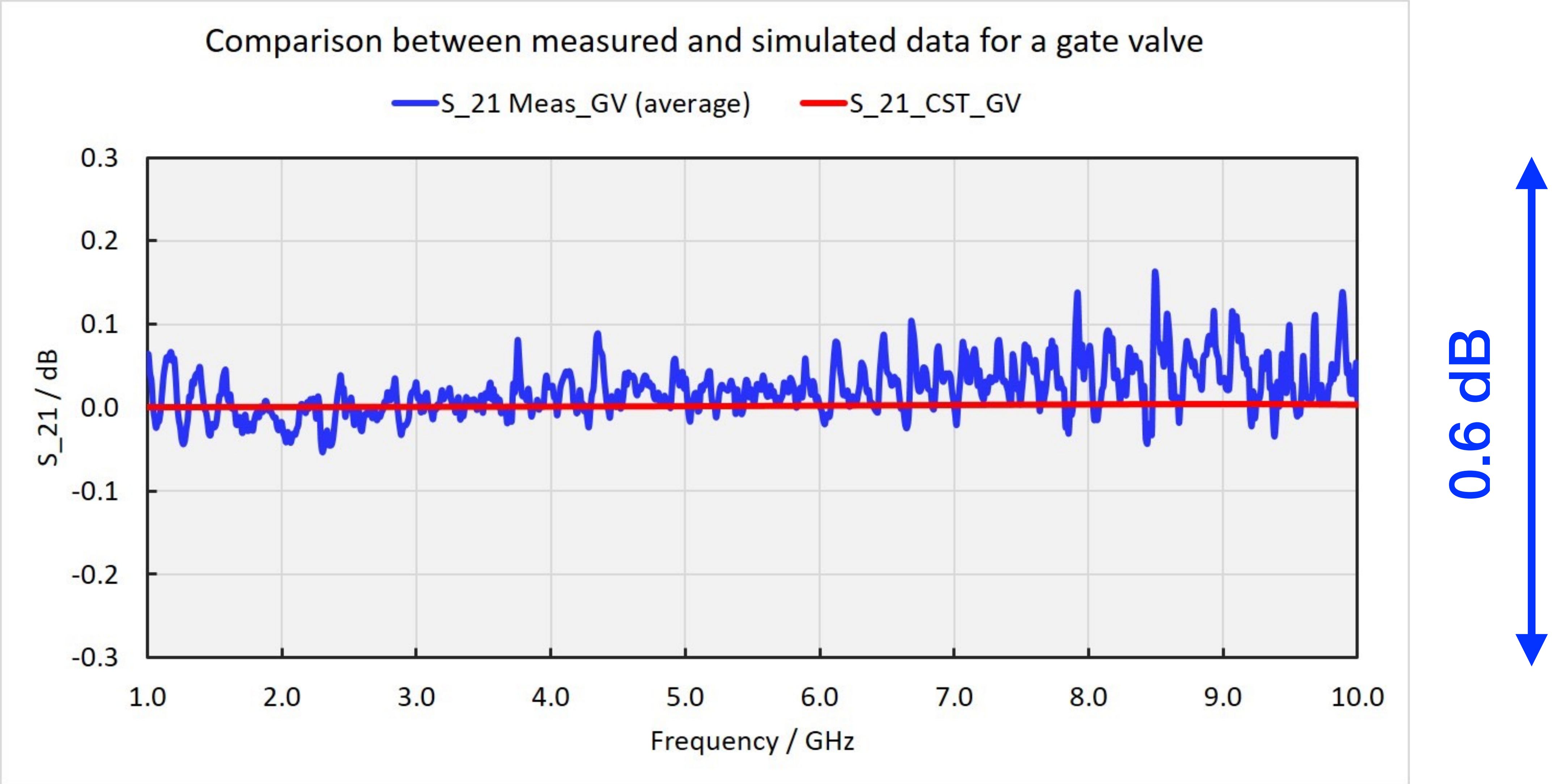




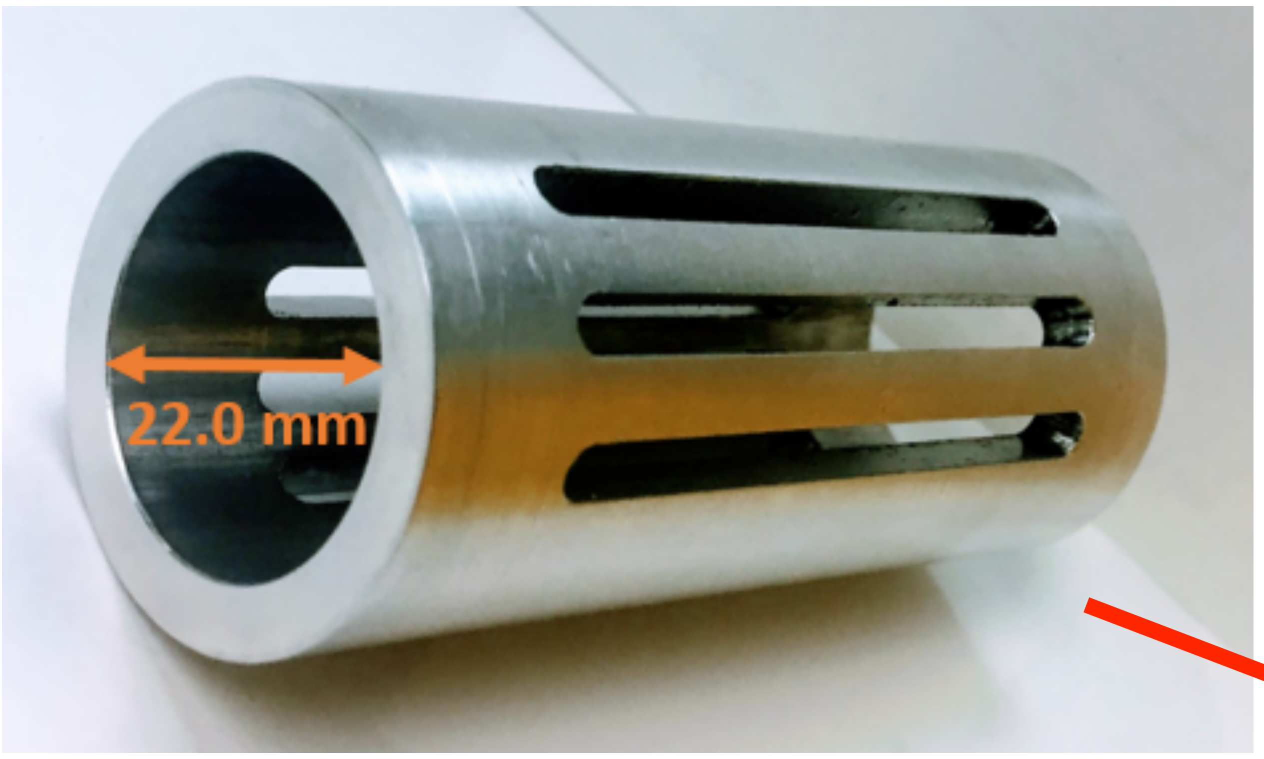
Appropriately Designed Components: Gate Valve Liner

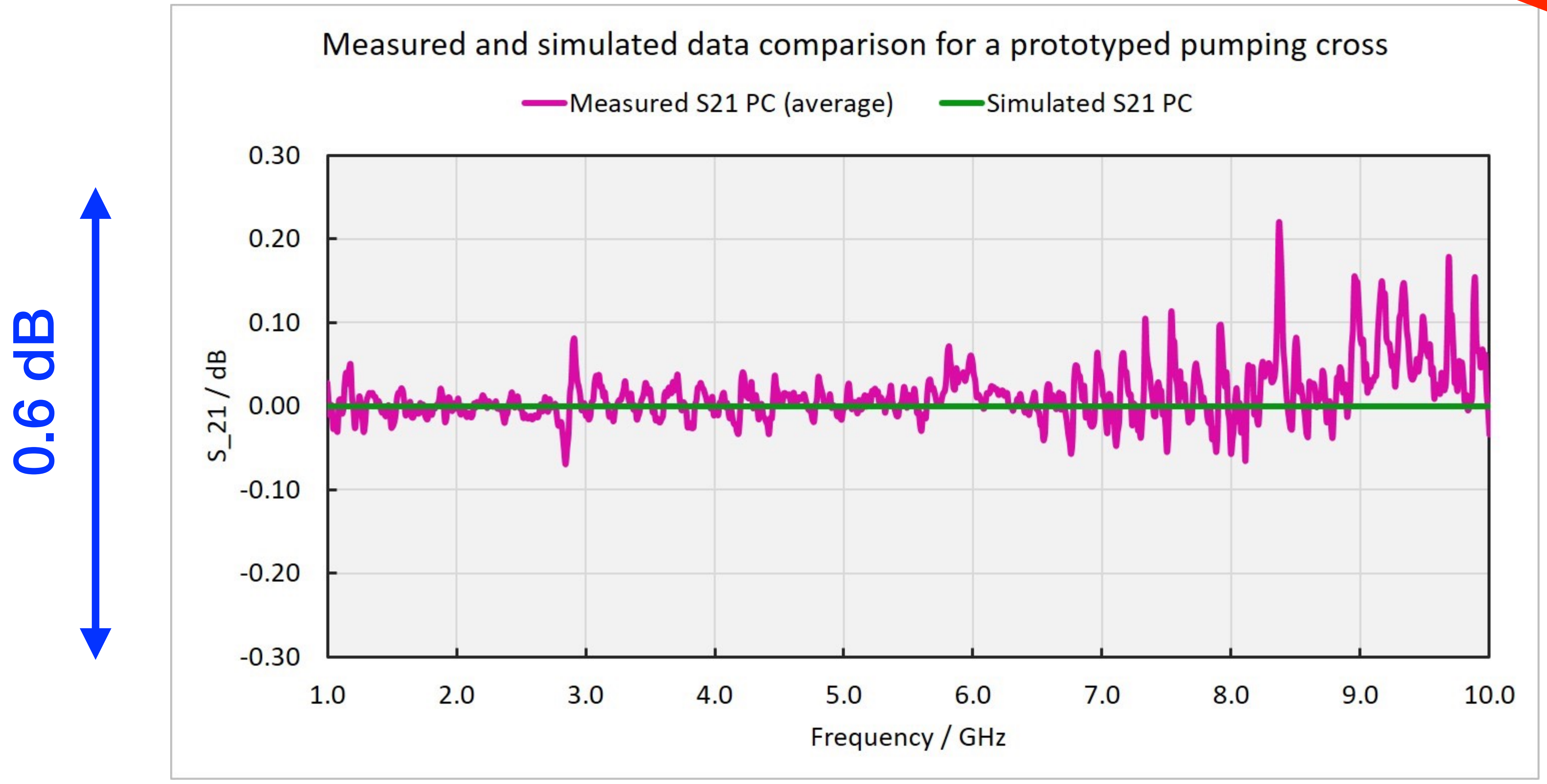
- Modern gate valves have RF-liners inside, but most of the vendors may not have RF-engineers to check the design specifications.

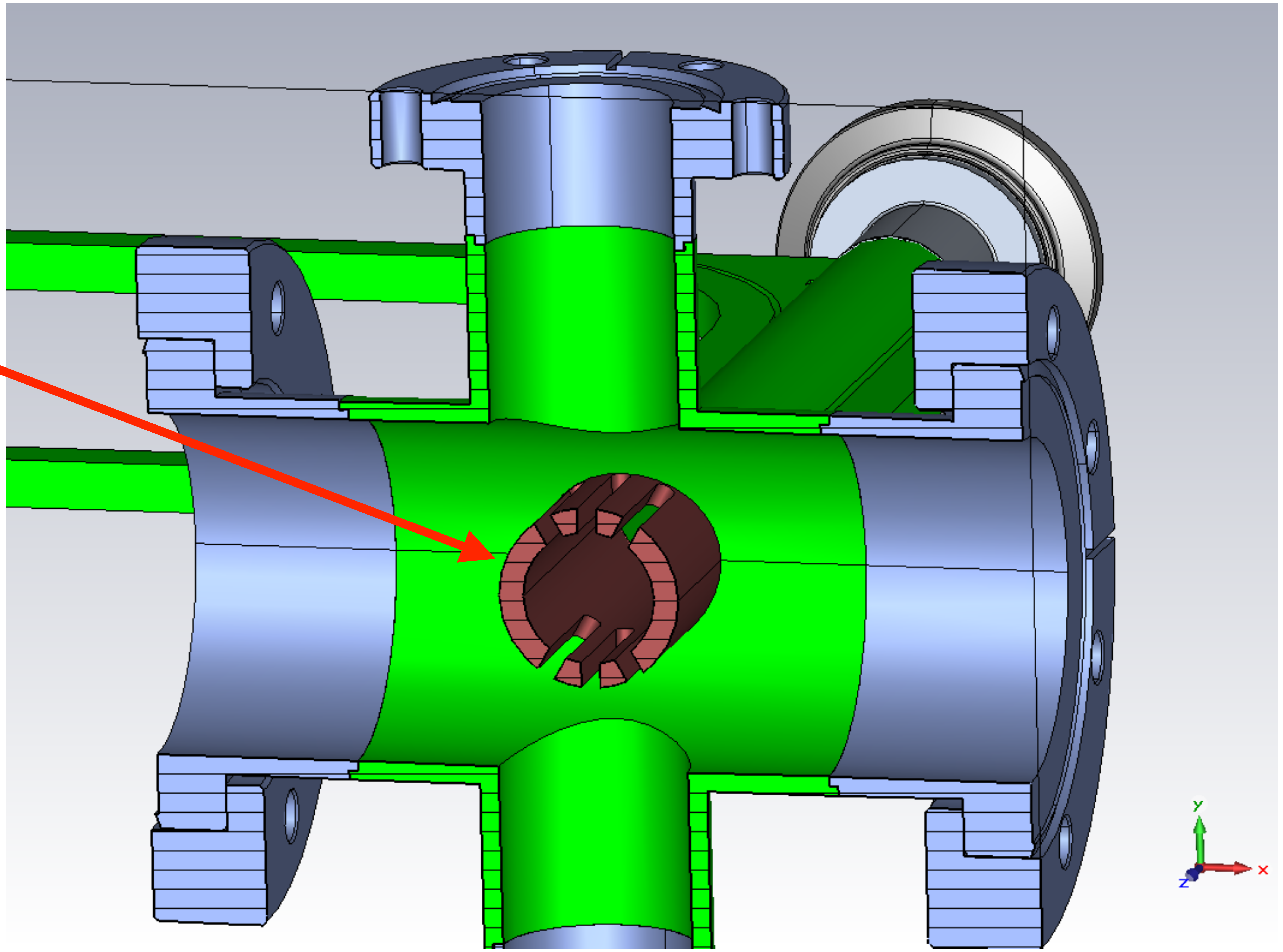




Appropriately Designed Components: Pumping Cross







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Summary

- Measured results of the NEG-coated chamber showed the effect of impedance due to the 1.5-micron thick is negligible below 29 GHz.
- The measured results of the APS-U BPM-bellows assembly, gate valve liner, and the pumping cross have been properly designed and manufactured to specifications, with no observable resonance peaks.
- On the other hand, impedance evaluations of several flange designs have displayed resonances that we subsequently attributed to improper machining and/or poor tolerance control, and we have worked to ensure future designs can be made to specifications.
- Finally, we demonstrated that the G-line is a relatively simple and, in our opinion, better way to measure the impedance over a broad frequency range.
- The research work that is still ongoing is the optimization and selection of proper gasket designs.

Acknowledgements

Advisors:
- Prof. Carlo Segre (IIT)
- Dr. Ryan Lindberg (Argonne)

Co-workers:
- Robert Lill
- Randall Zabel
- Jason Carter
- Benjamin Stillwell
- Xiang Sun
- John Noonan

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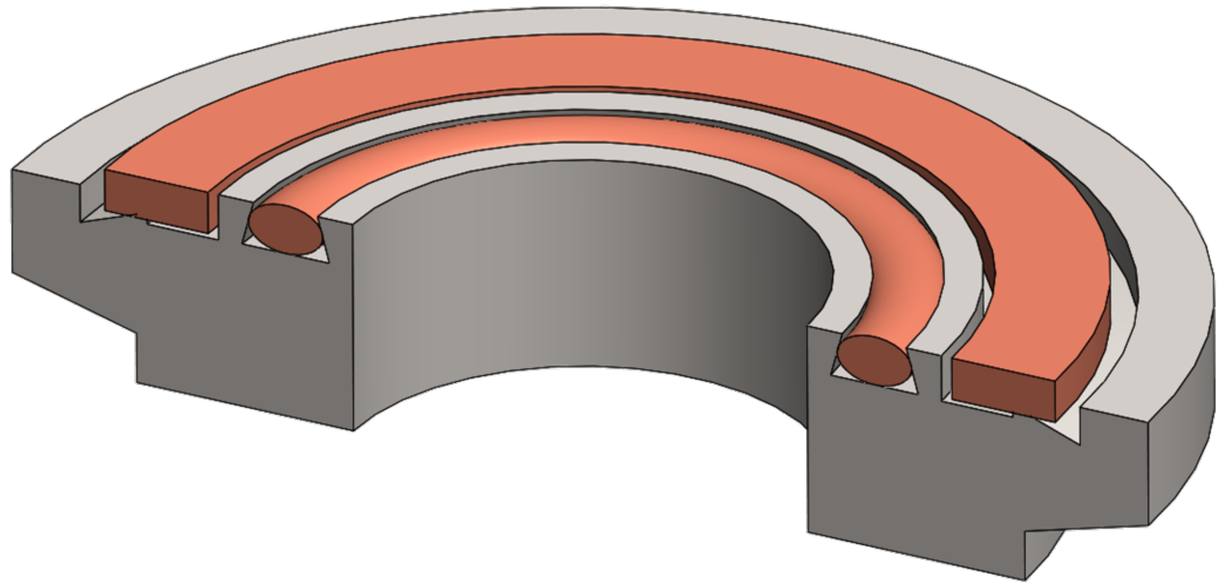
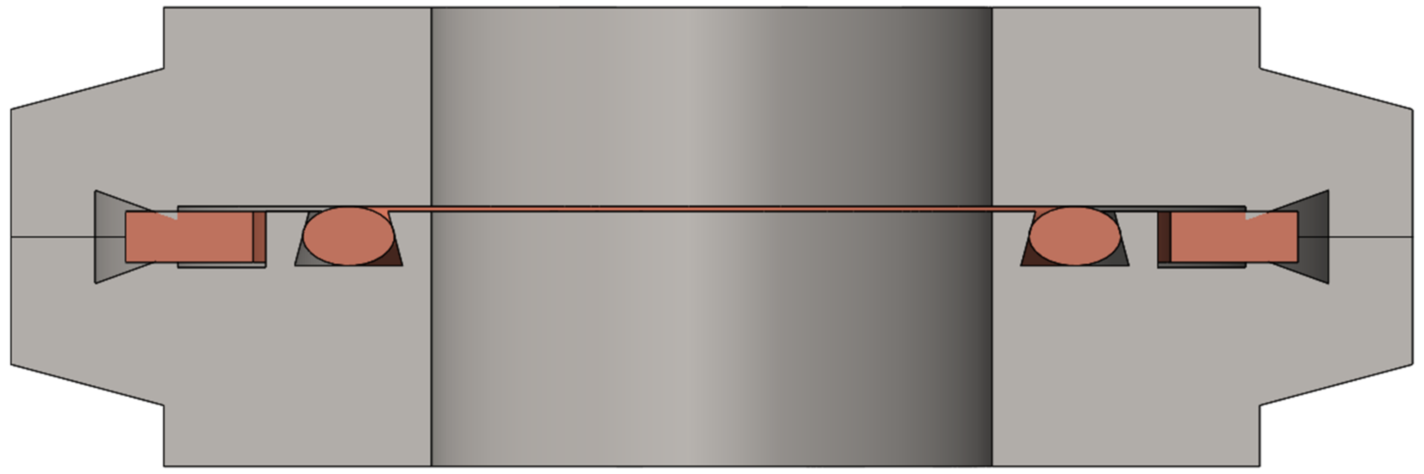
Thank you all for your time and attention.

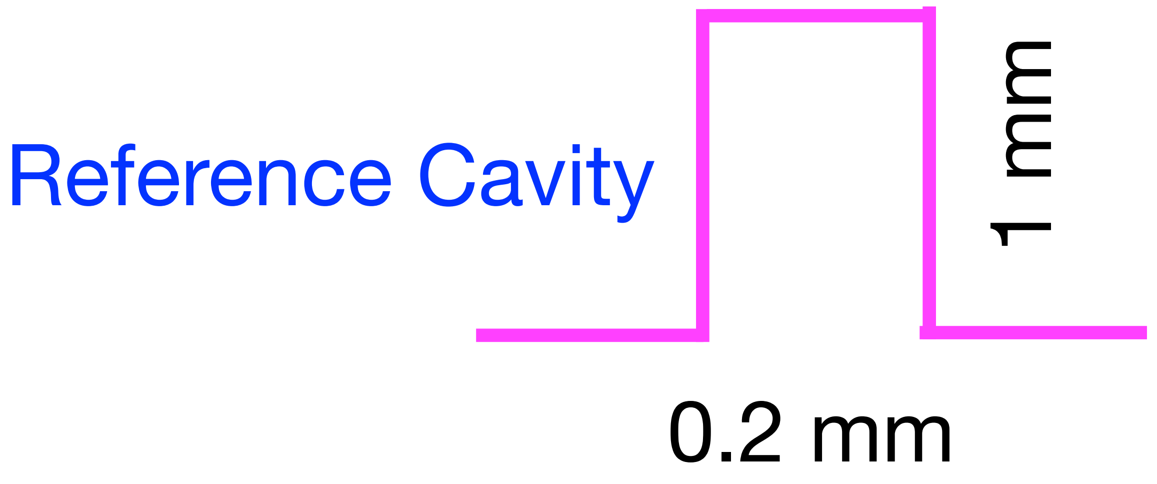
Questions, comments, feedbacks ??

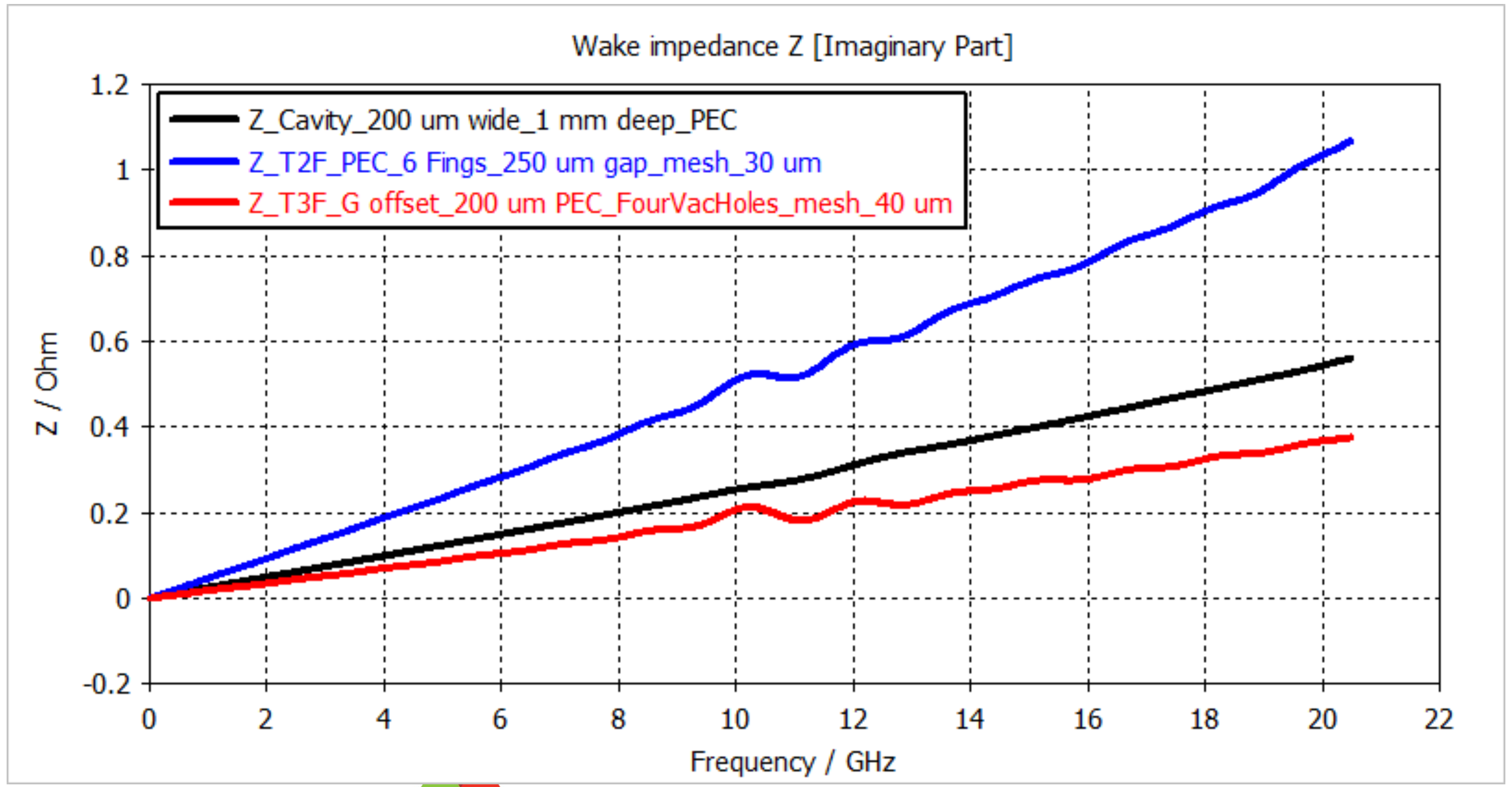
Comparison of gaskets performance

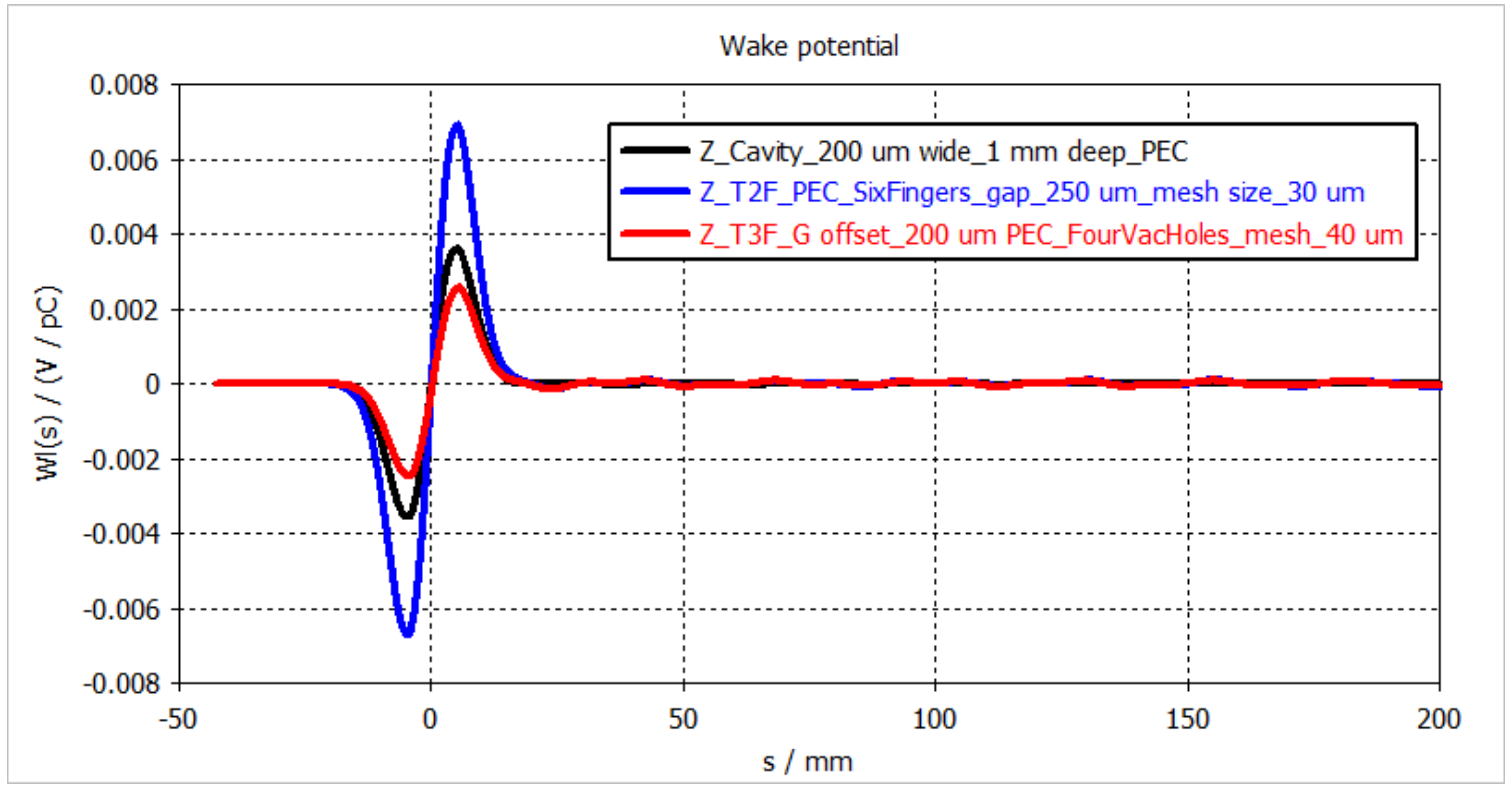
- Type 1 gasket is removed from the consideration due to the possible difficulty arises during installation or replacement.











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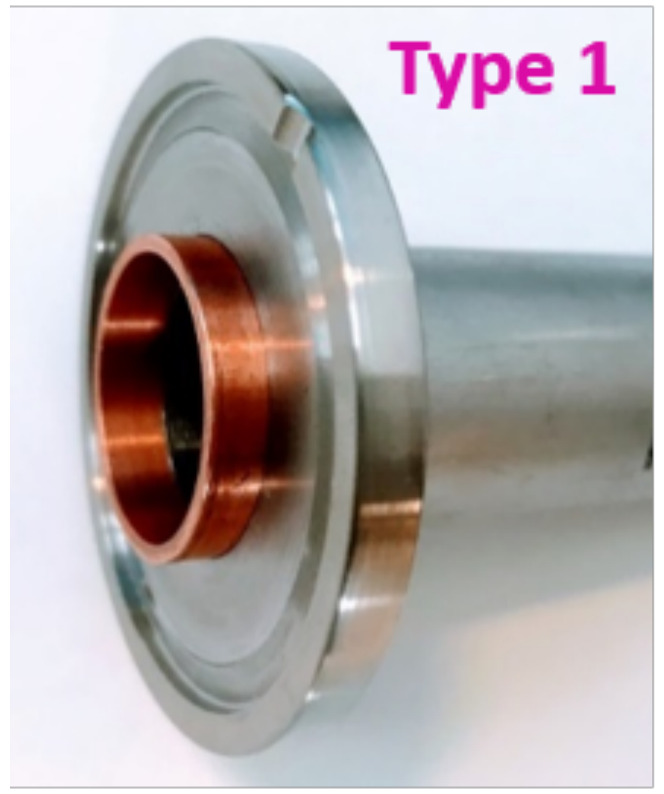

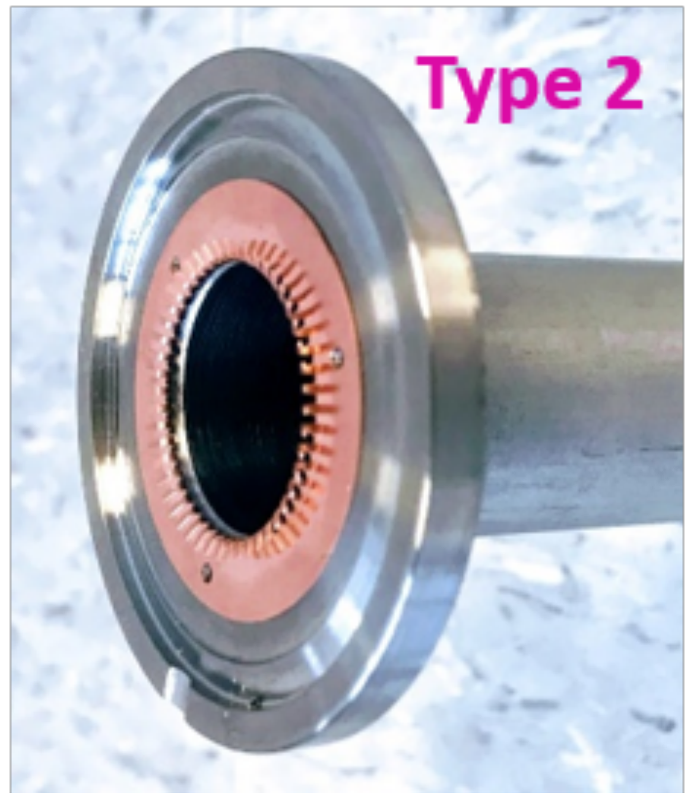

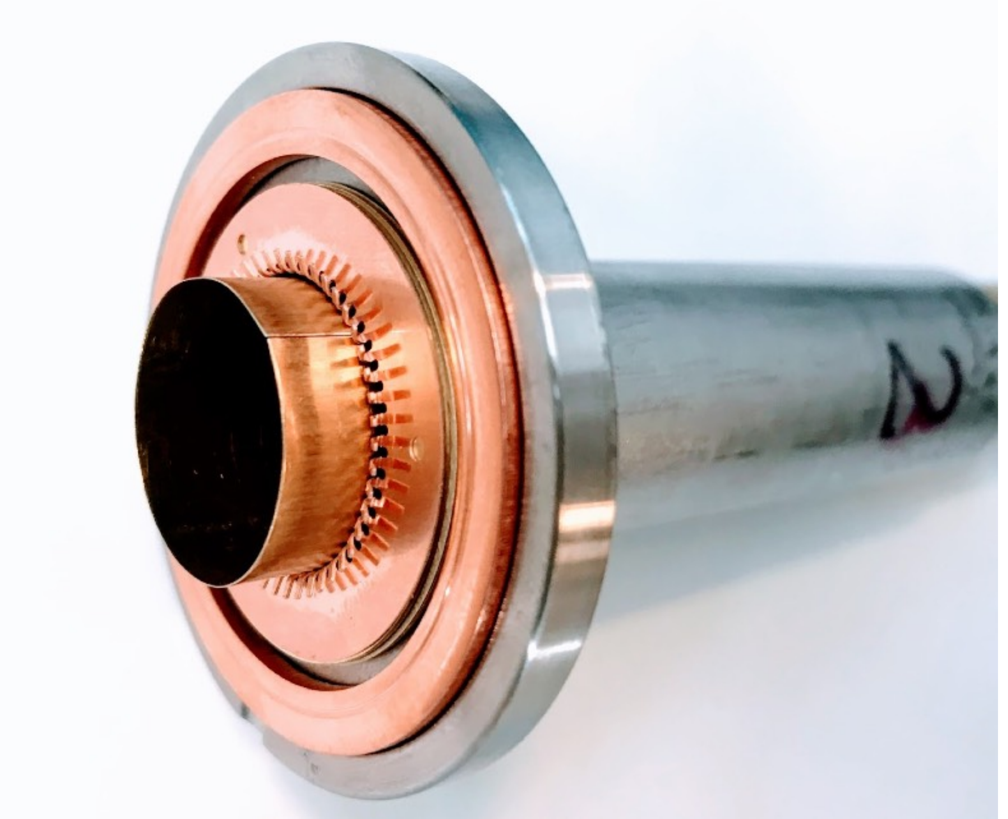

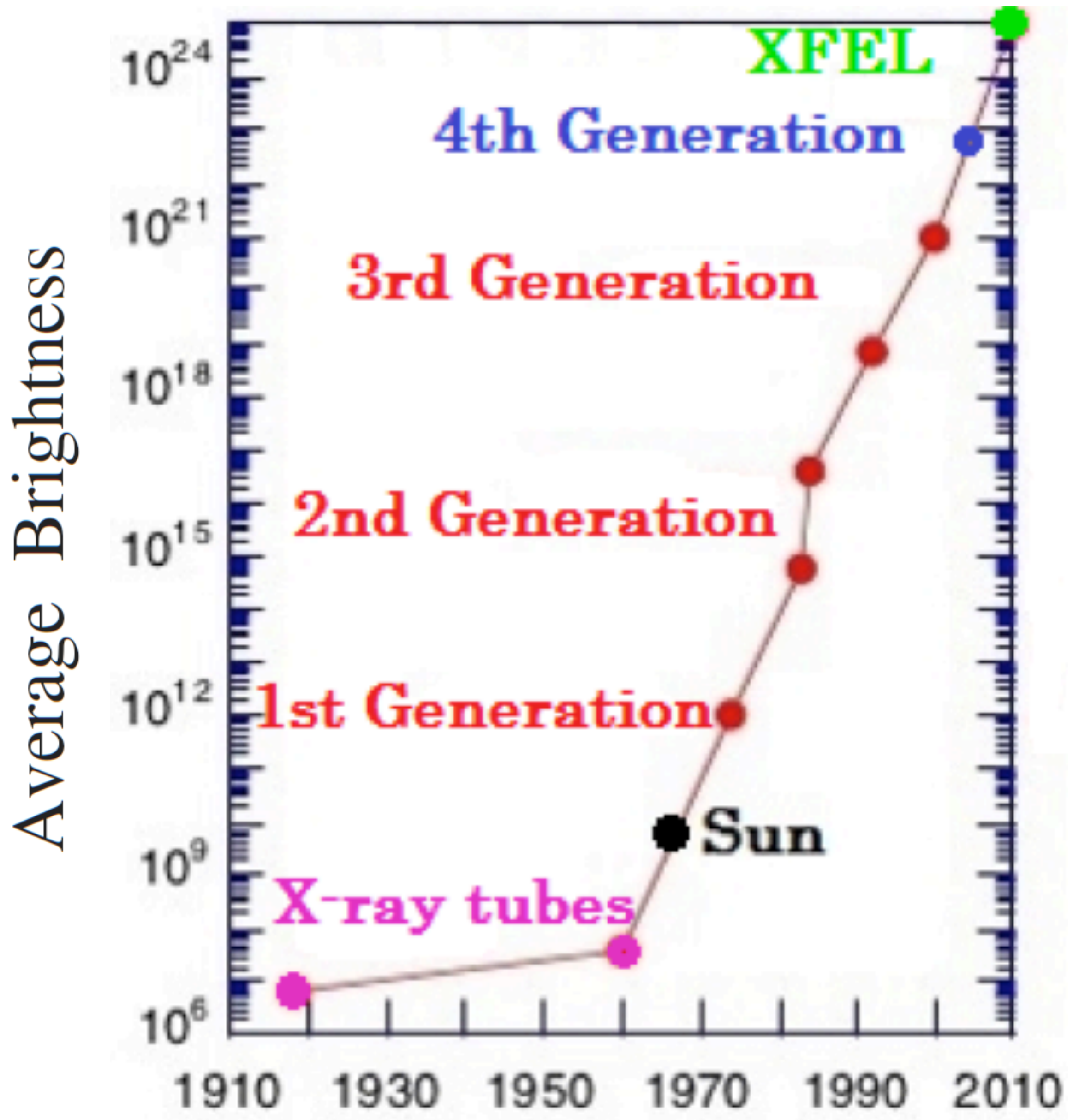

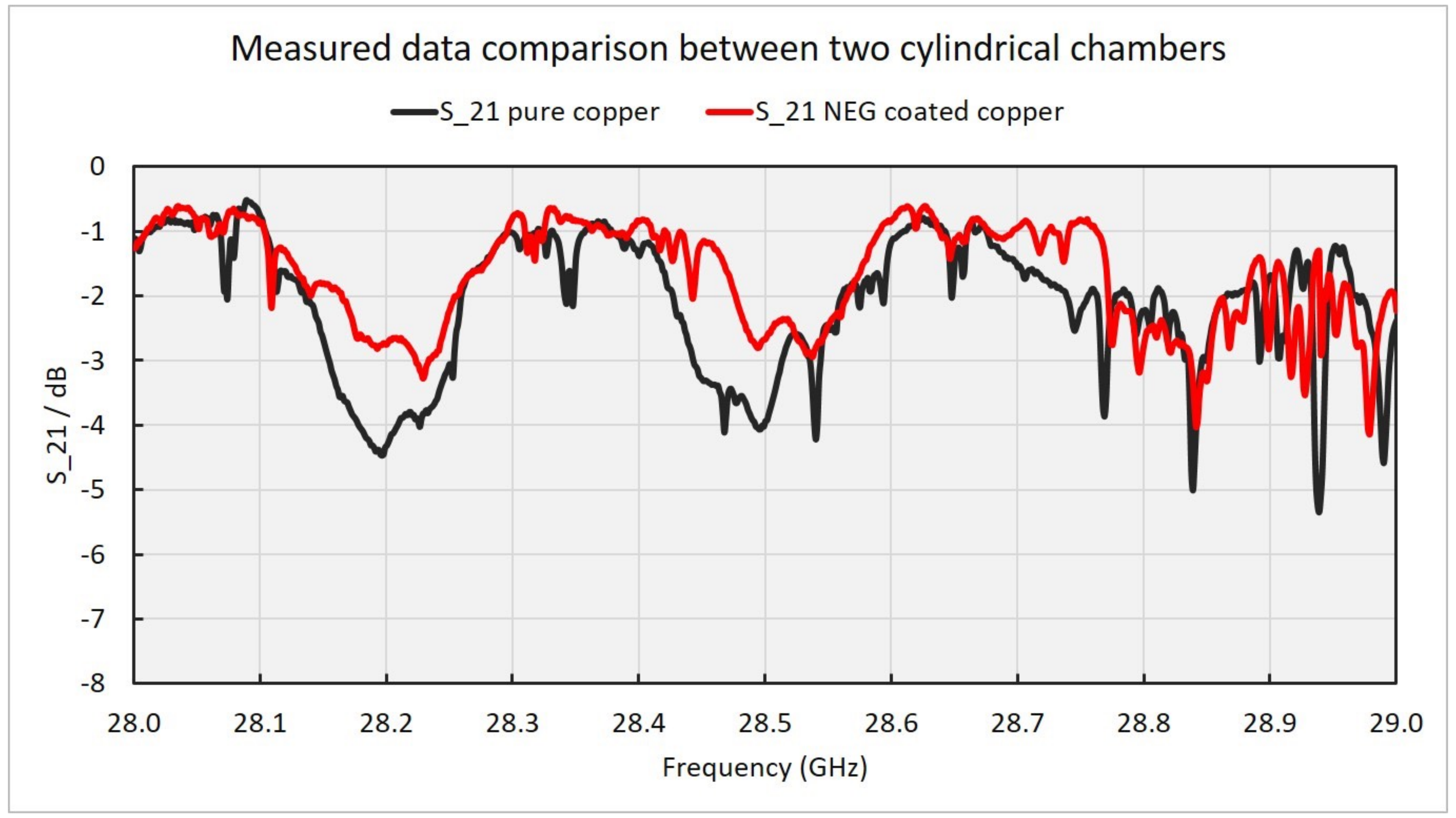

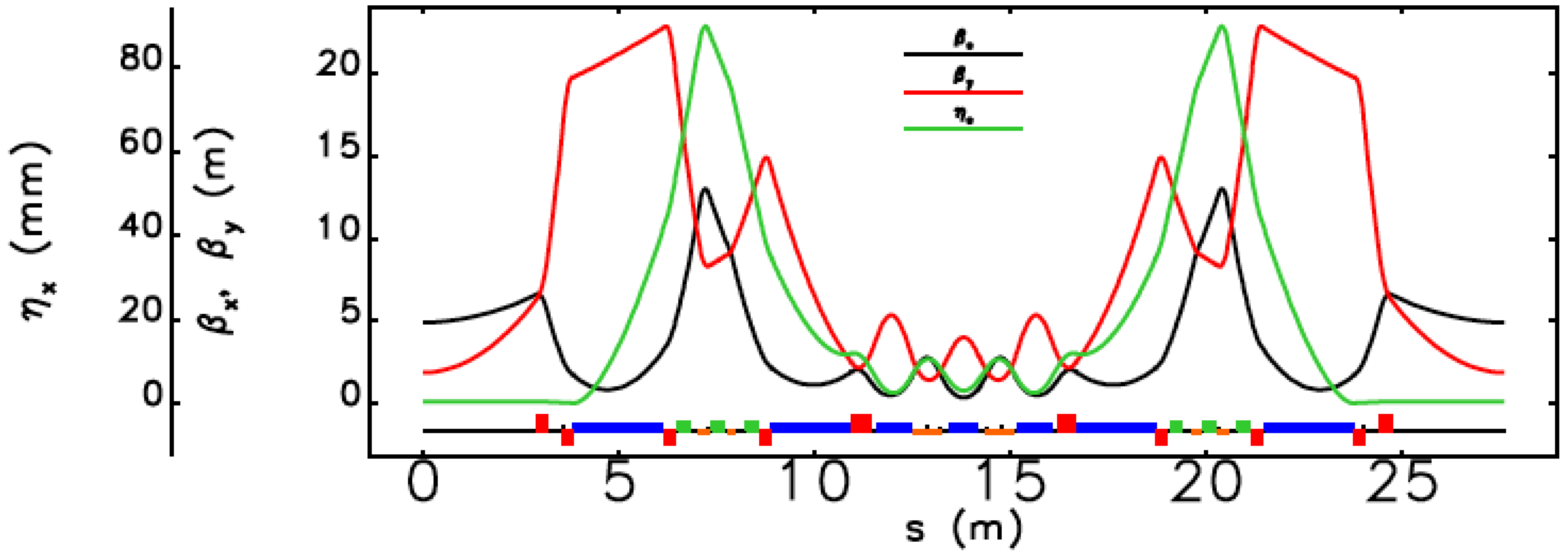

Figure 4.2. Hybrid 7BA lattice with reverse bends for the APS. The natural emittance is 42 pm. Blue blocks represent normal-direction dipoles, orange blocks represent reverse-direction dipoles, red blocks represent quadrupoles, and green blocks represent sextupoles.

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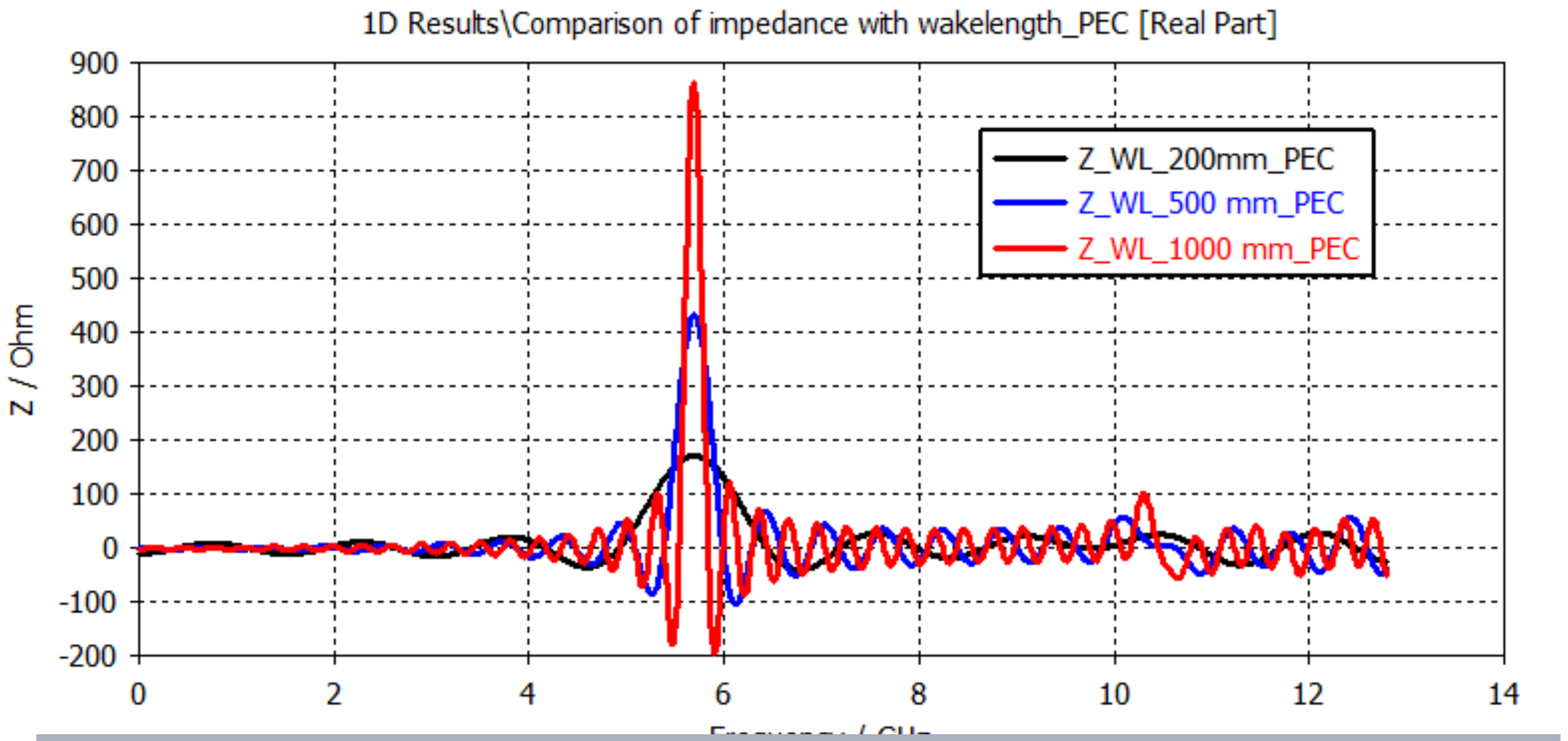
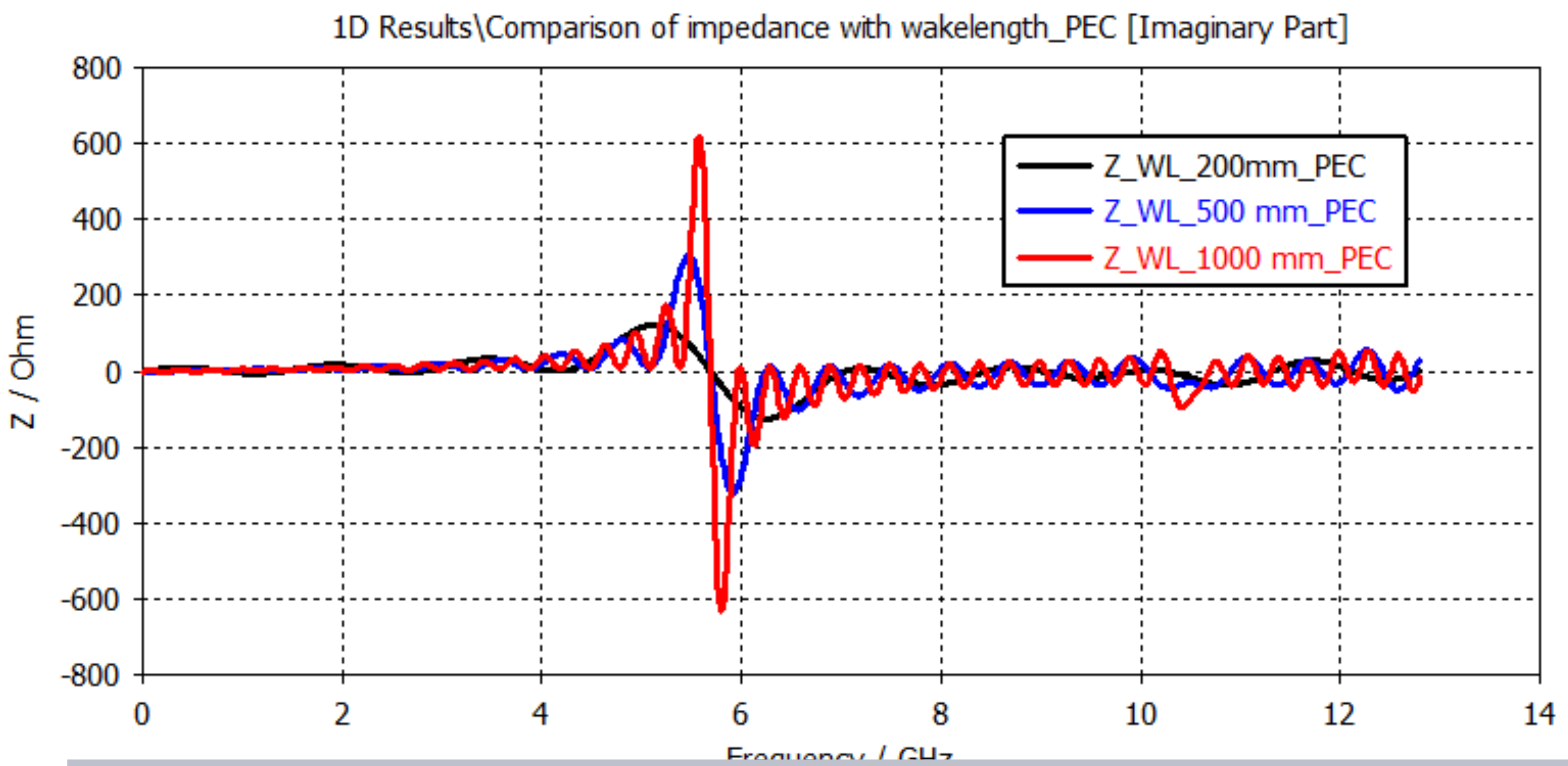
- I think a postdoc position is a transition phase for a researcher where he/she can transform from learning to leading phase.

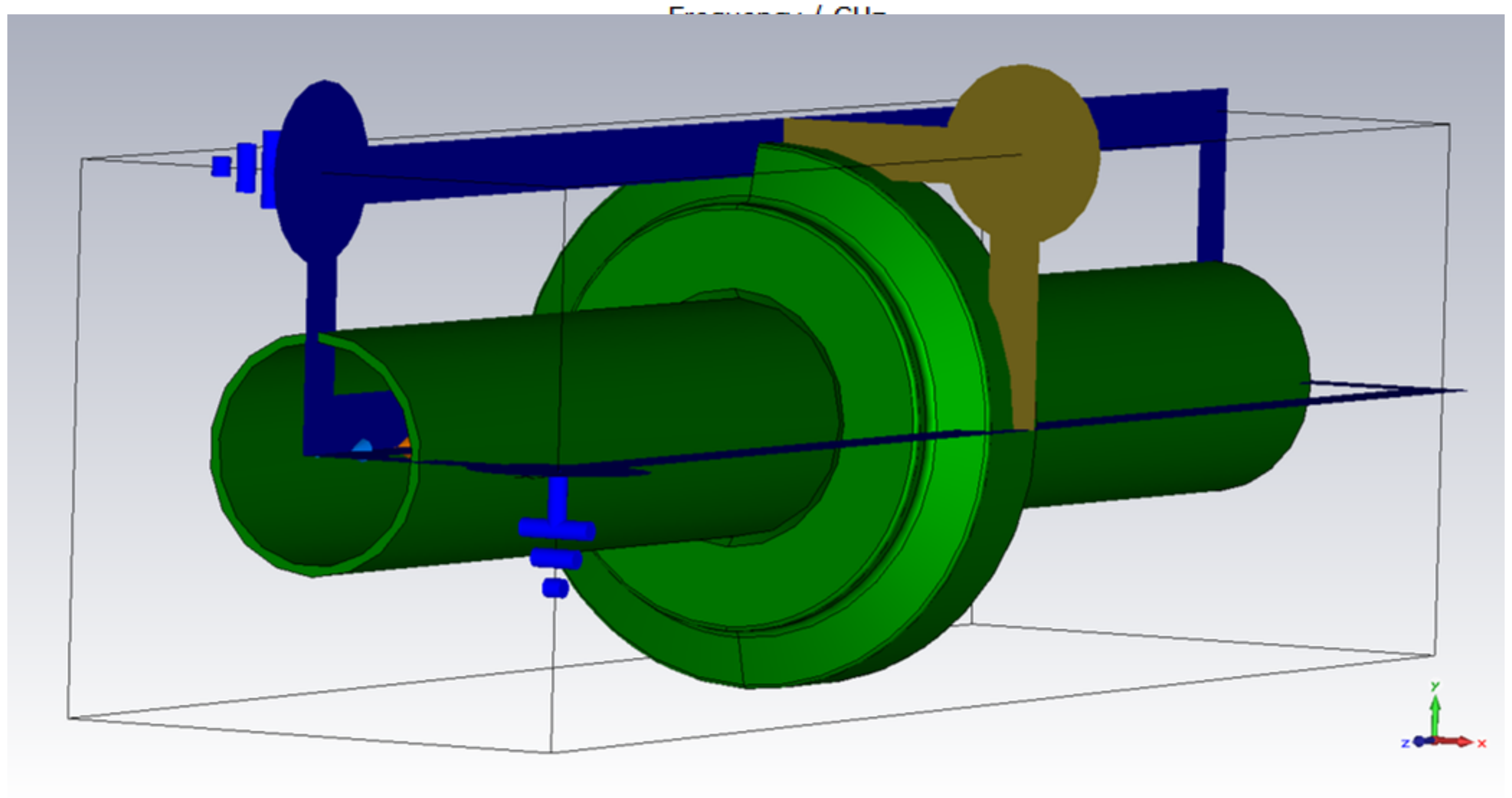
Table 4.1. Beam parameter comparison.

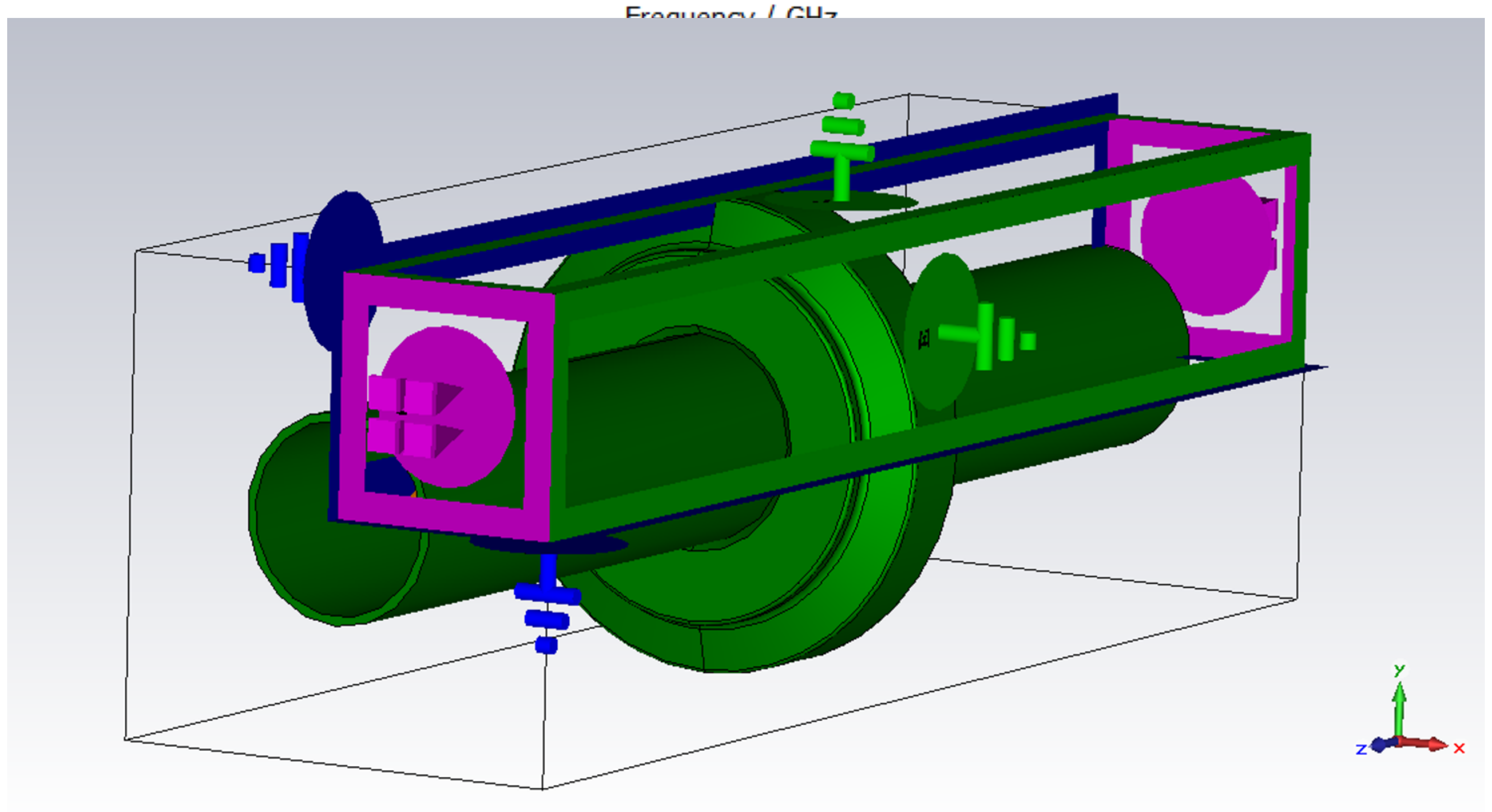
Quantity	APS Now	APS MBA Timing Mode	APS MBA Brightness Mode	Units
Beam Energy	7	6	6	GeV
Beam Current	100	200	200	mA
Number of Bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Emittance Ratio	0.013	1	0.1	
Horizontal Emittance	3100	31.9	42.2	pm-rad
Horizontal Beam Size (rms)	275	12.6	14.5	μm
Horizontal Divergence (rms)	11	2.5	2.9	μrad
Vertical Emittance	40	31.7	4.2	pm-rad
Vertical Beam Size (rms)	10	7.7	2.8	μm
Vertical Divergence (rms)	3.5	4.1	1.5	μrad

Backup slides









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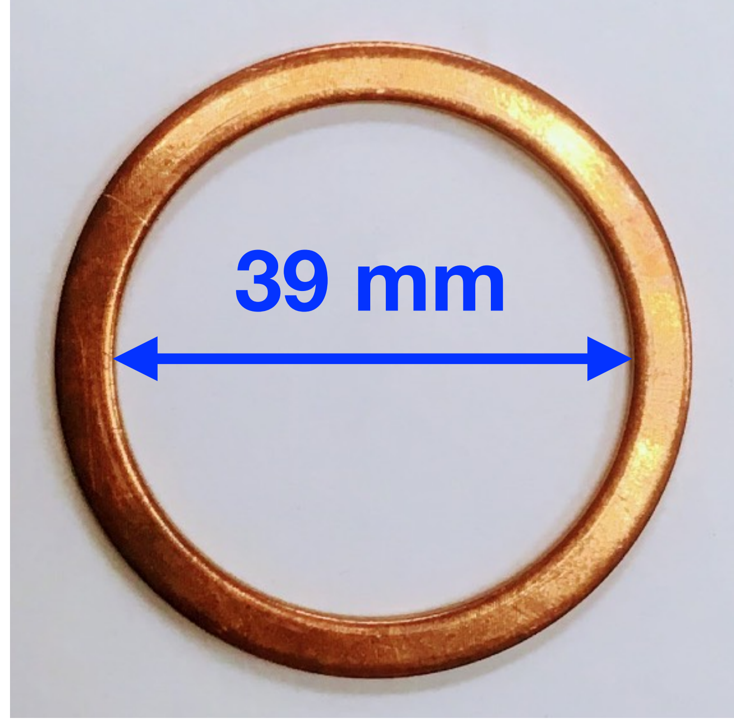
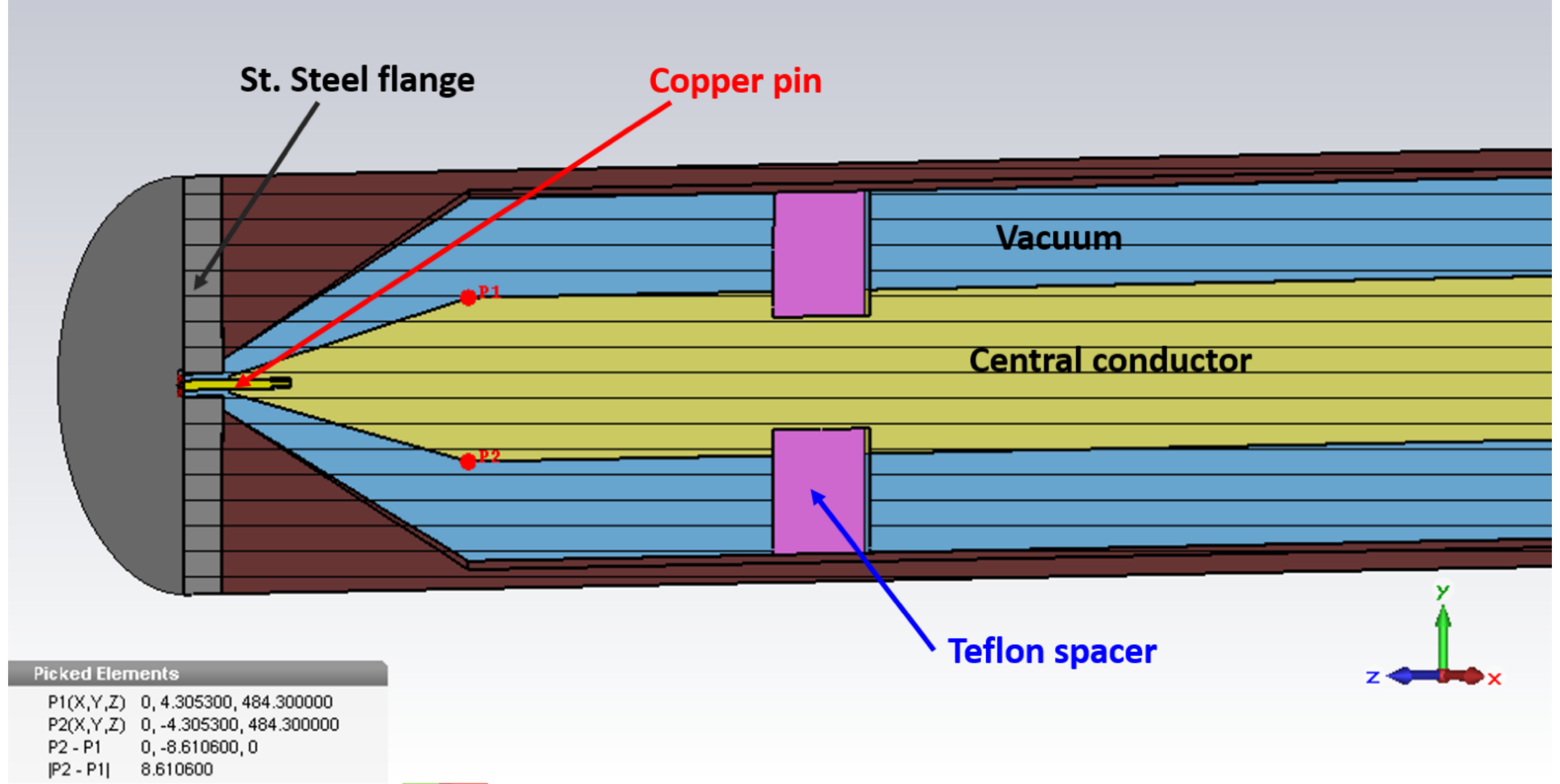
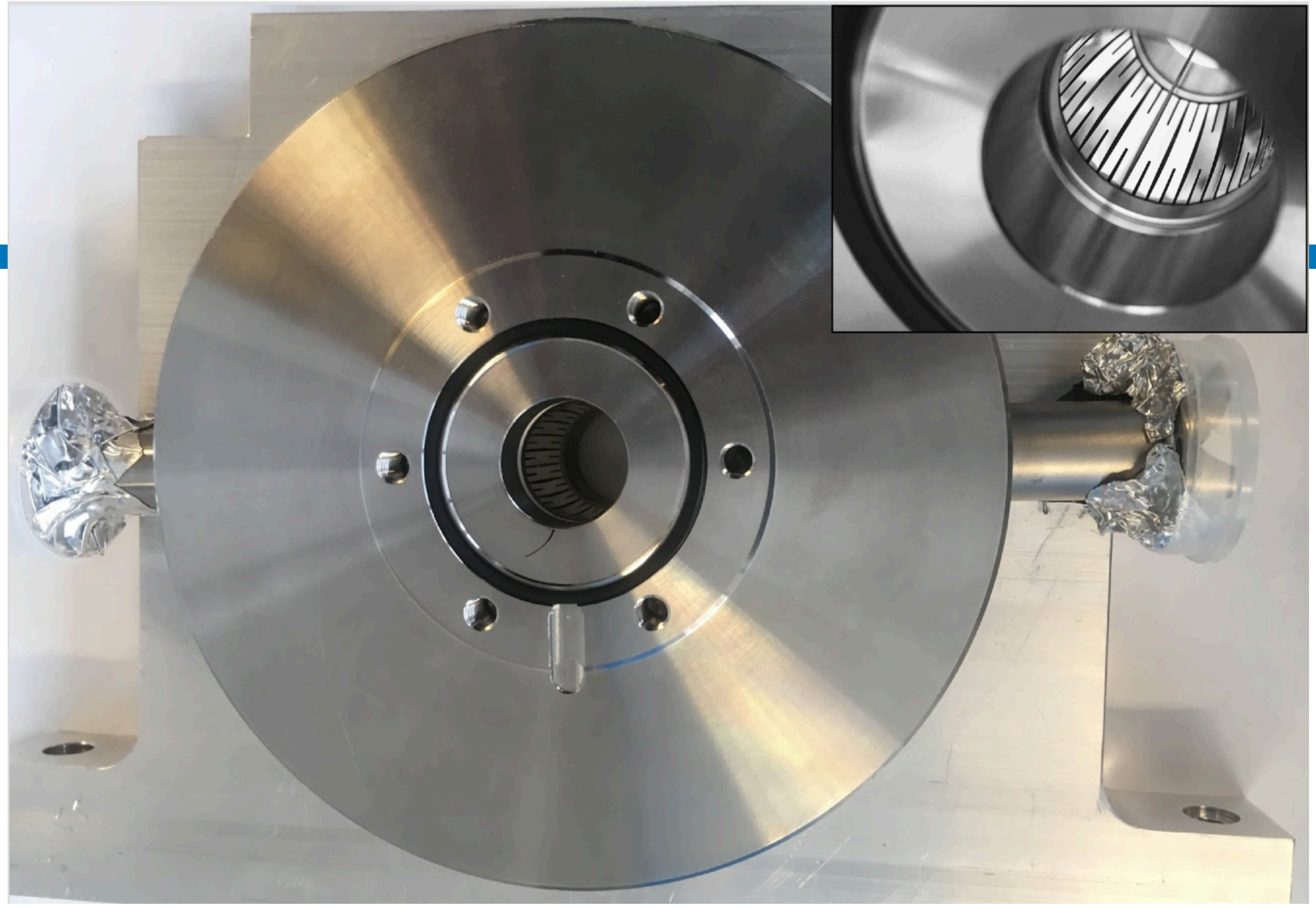
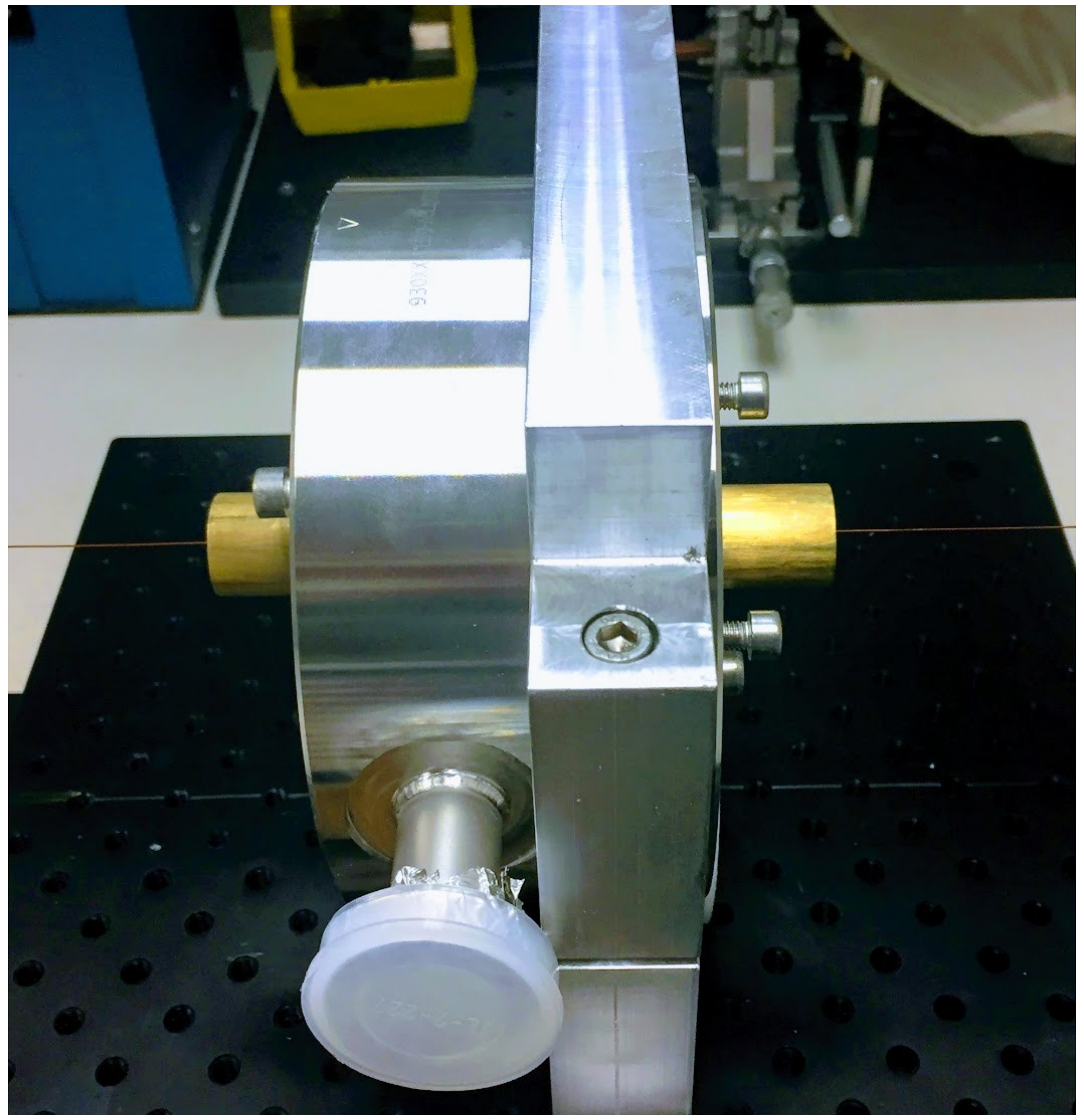
Standard









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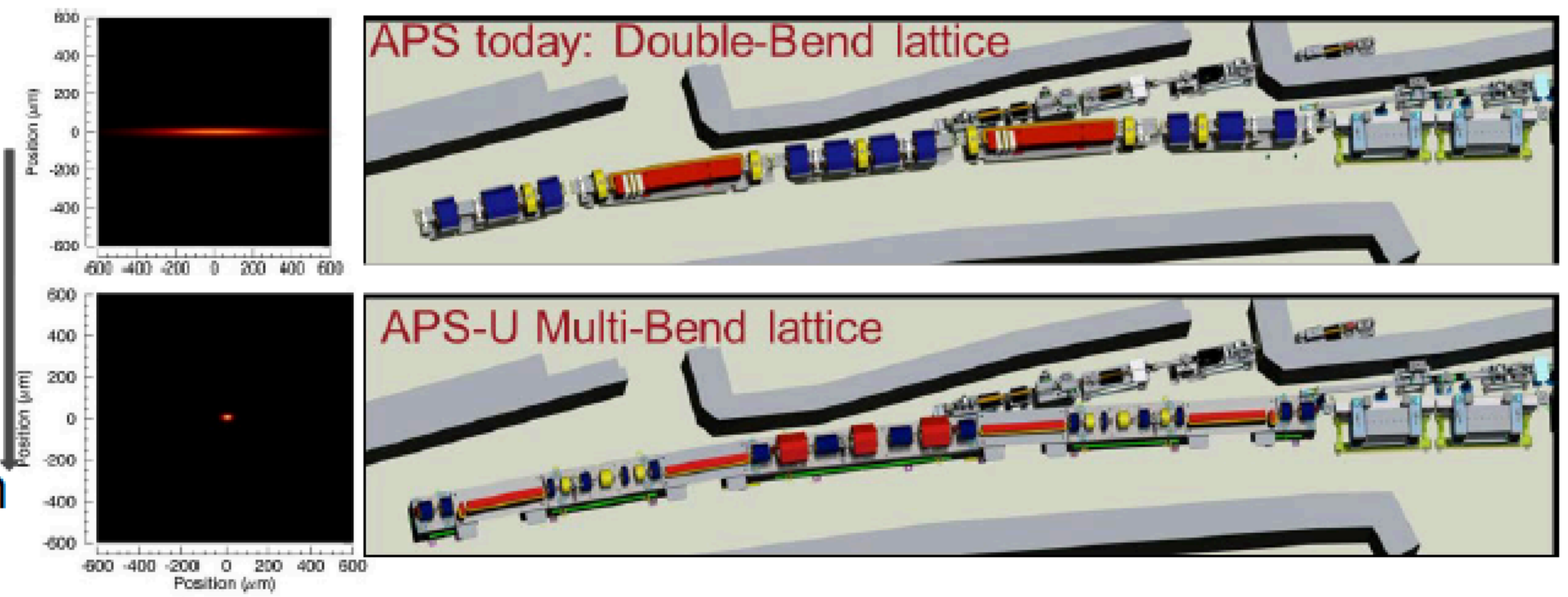
Slide screen shot: Bob Hettel presentation

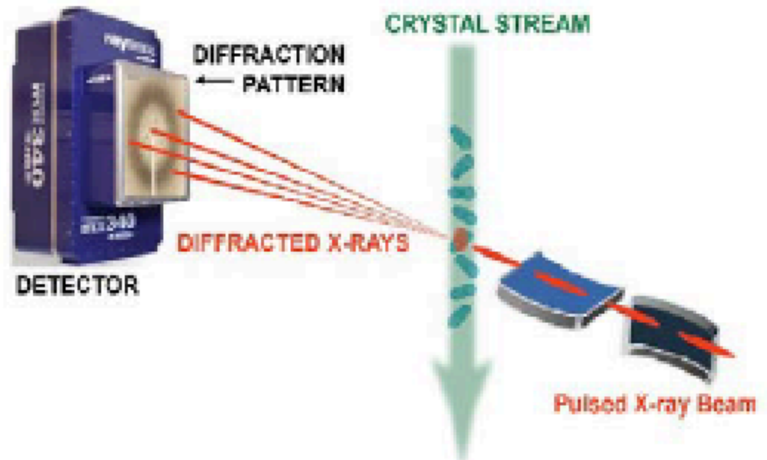
THE APS Upgrade: Building a world leading hard x-ray facility

- Design optimized to provide orders of magnitude improvements in brightness, coherent flux, and nano-focused flux
- MBA lattice optimized with reverse bends, reduces emittance from 67 pm to 42 pm
- Beamline proposal selection and roadmap complete
- Technical prototypes well along; Preliminary Design Report complete; procurements starting



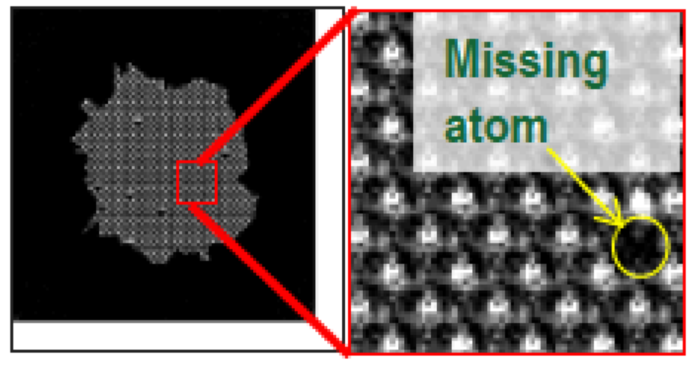
Small-Beam Scattering & Spectroscopy

Nanometer imaging with chemical and structural contrast; few-atom sensitivity
Room-temperature, serial, single-pulse pink beam macromolecular crystallography



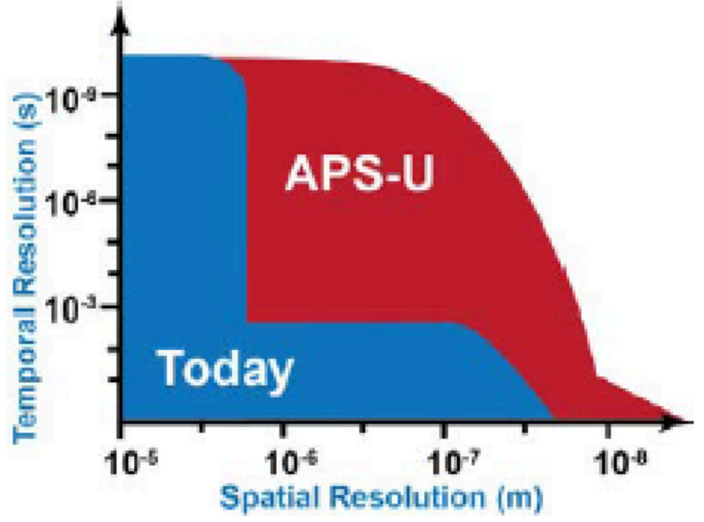
Coherent Scattering & Imaging

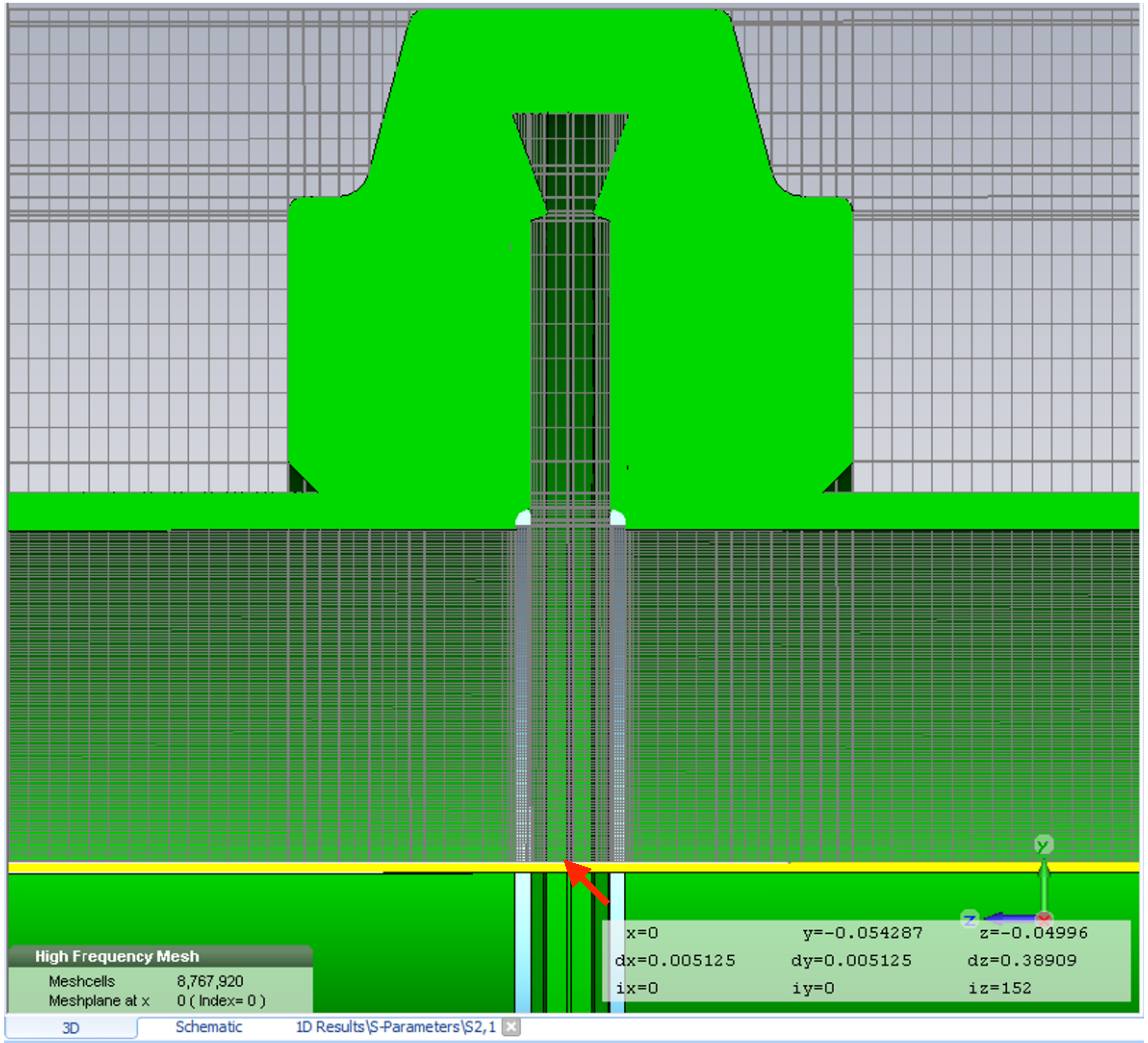
Highest possible spatial resolution: 3D visualization; imaging of defects, disordered heterogeneous materials
XPCS to probe continuous processes from nsec onward, opening up 5 orders of magnitude in time inaccessible today,



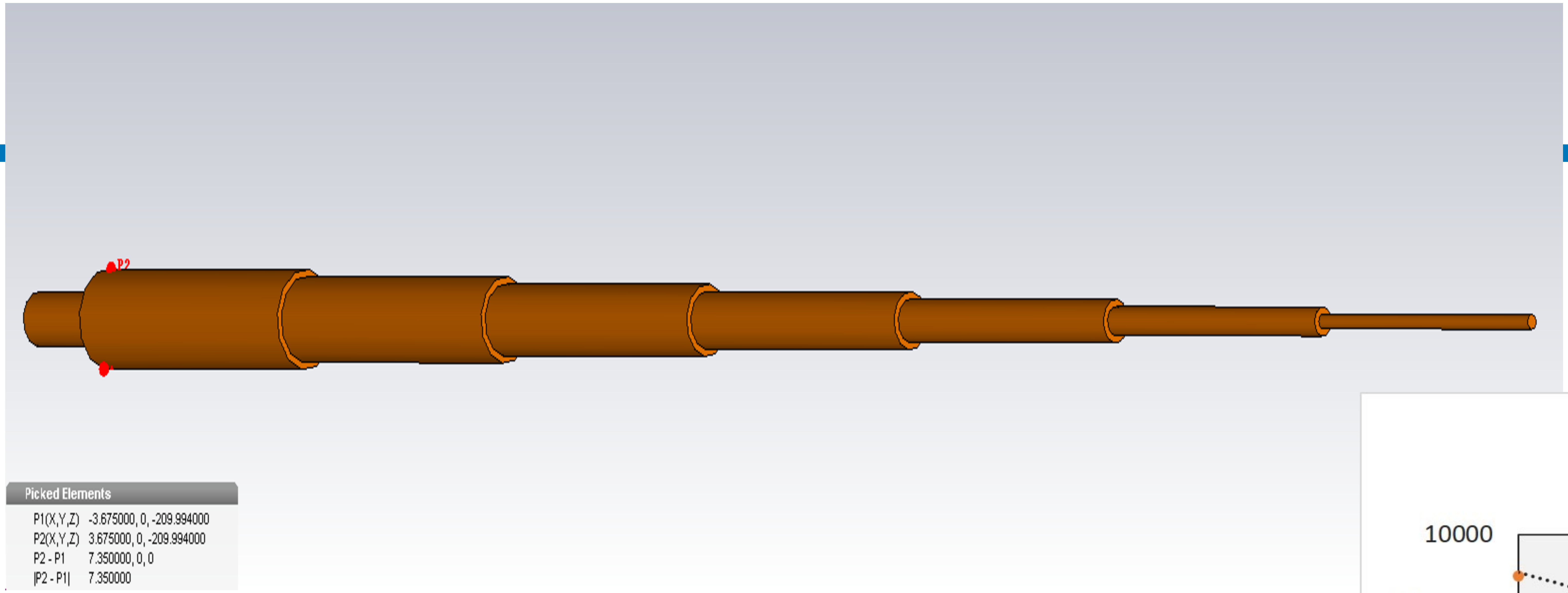
Resolution @ Speed

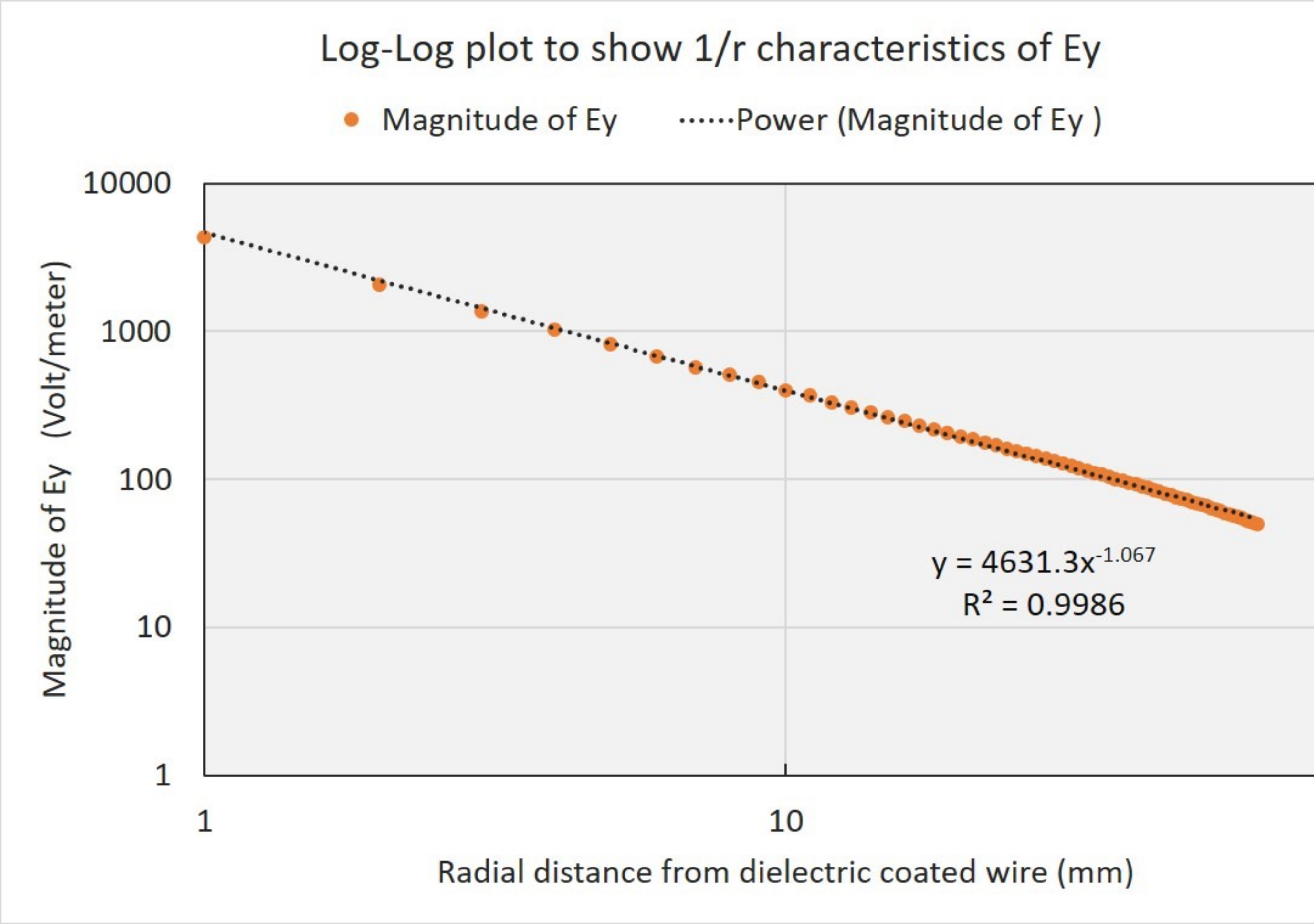
Mapping all of the critical atoms in a cubic millimeter
Detecting and following rare events
Multiscale imaging: enormous fields of view with high resolution





High Frequency Mesh
Meshcells 8,767,920
Meshplane at x 0 (Index= 0)
x=0 y=-0.054287 z=-0.04996
dx=0.005125 dy=0.005125 dz=0.38909
ix=0 iy=0 iz=152
3D
Schematic
1D Results\S-Parameters\S2,1





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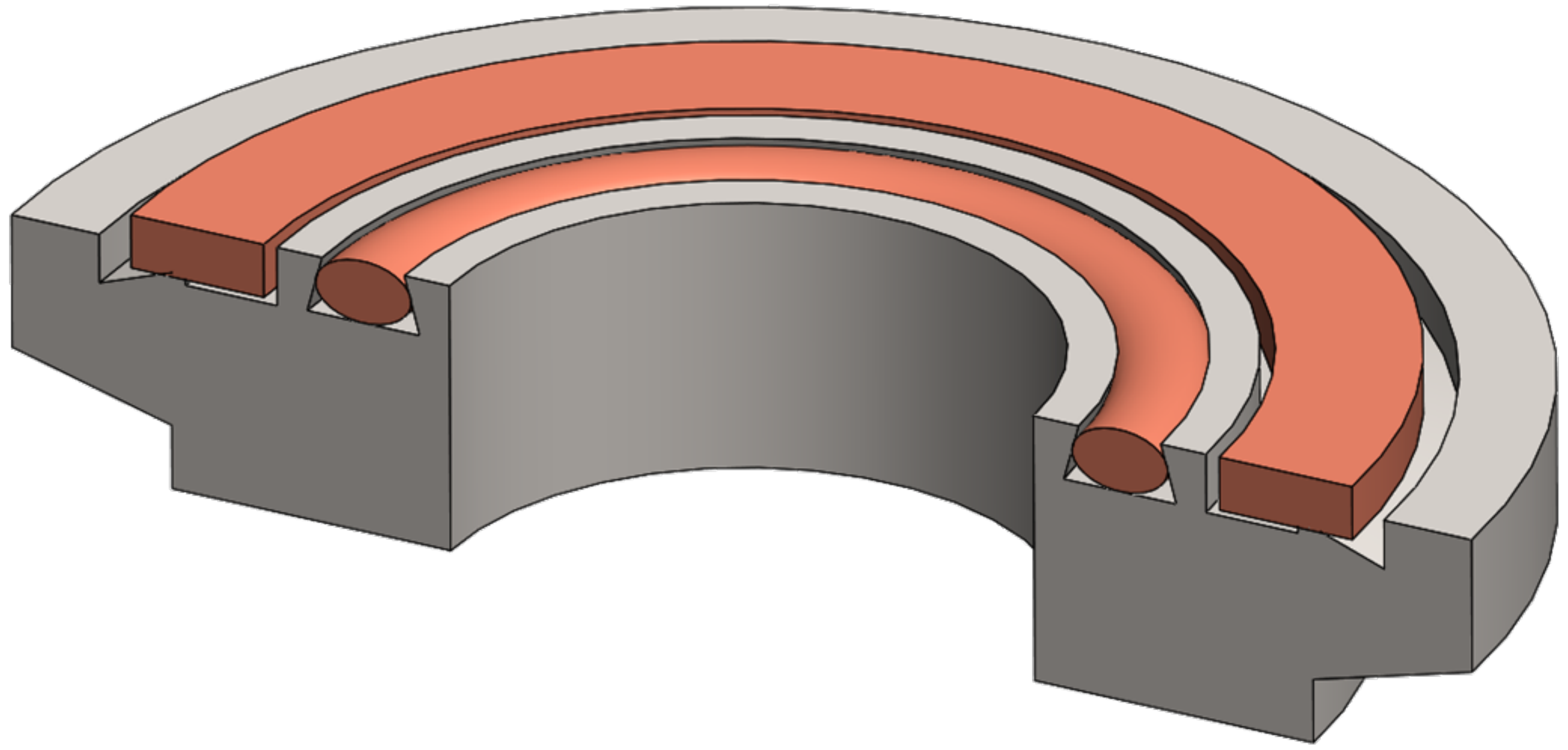
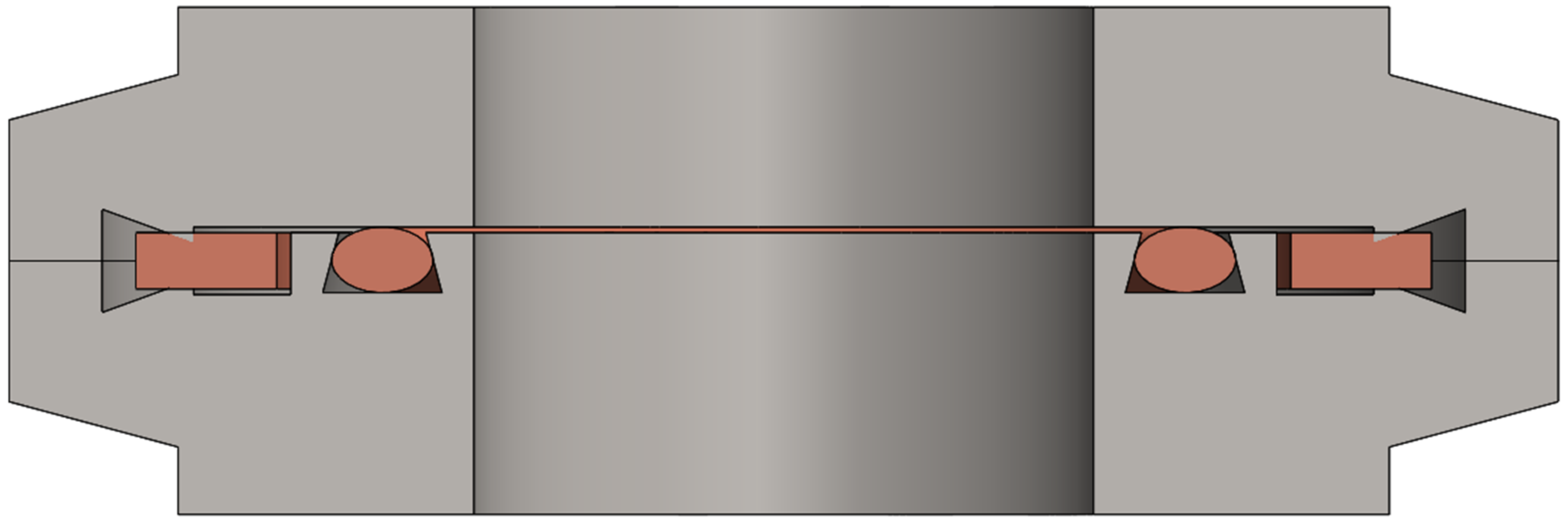
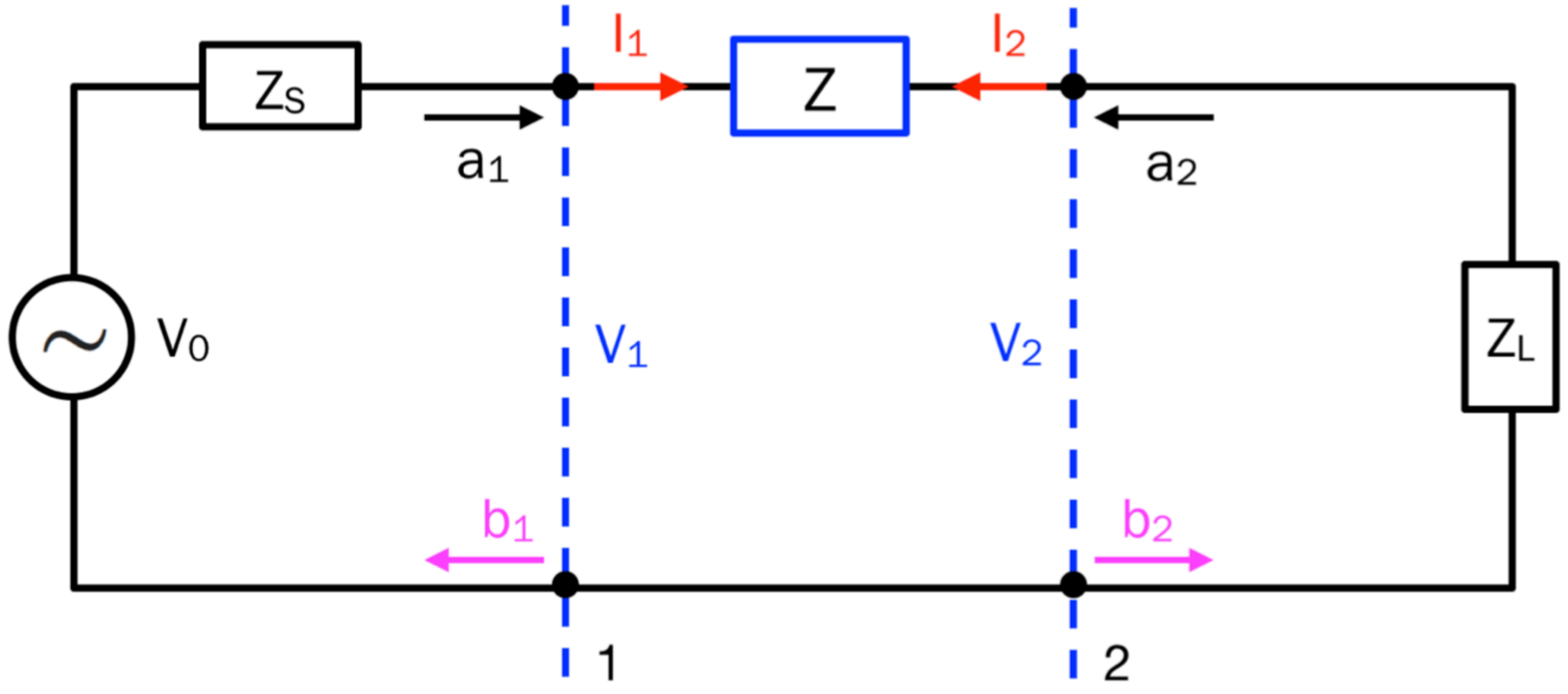
- RFQ is a linear accelerator that can focus, bunch and accelerate a continuous beam of charged particles at low energy with high bunching and transmission efficiency.







$$V_1 = I_1(Z + Z_L)$$

$$V_2 = -I_2 Z_L$$

$$I_1 = \frac{V_0}{Z_s + Z + Z_L}$$

$$I_2 = -I_1$$

$$a_i = \frac{V_i + I_i Z_0}{2\sqrt{Z_c}}$$

$$b_i = \frac{V_i - I_i Z_0^*}{2\sqrt{Z_c}}$$

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