Impedance Study Examples at CERN

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Dr. Hikmet BURSALI

hikmetbursali@gmail.com

Working Areas

Electromagnetic Design & Optimization
RF & System Engineering

Background

Sapienza University of Rome, PhD
Department of Basic and Applied Sciences for Engineering (SBAI), Accelerator Physics

Izmir Institute of Technology, MSc,
Department of Engineering
Electronics & Communication Engineering

Izmir Institute of Technology, BSc,
Department of Engineering
Electronics & Communication Engineering

Experience

Senior Fellow (CERN, SY-RF-BR)
Impedance Team

Doctoral Student (CERN, SY-RF-MKS)
CLIC Structure Fabrication Group

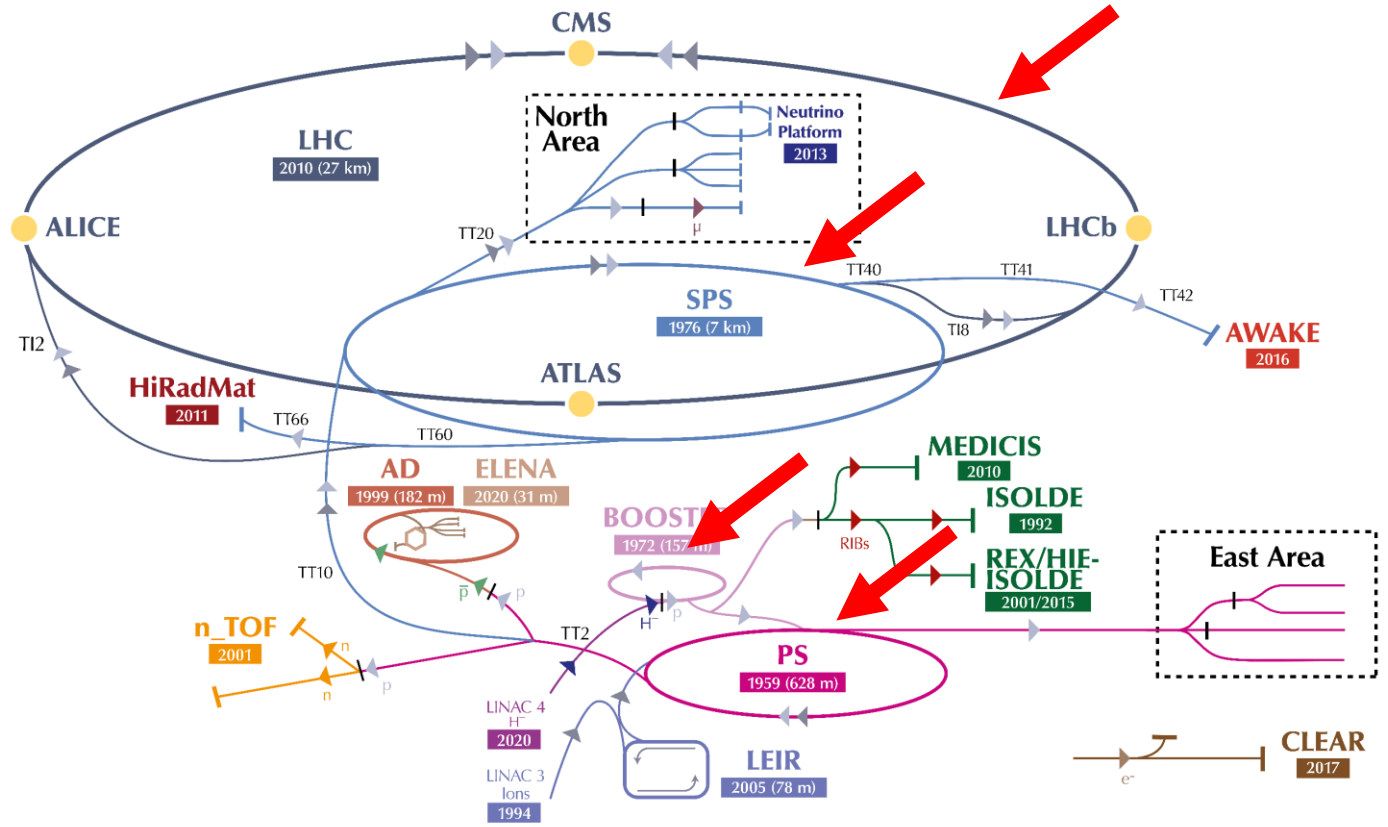
Technical Student (CERN, BE-RF-MK)
CLIC Structure Fabrication Group

Teaching Assistant & Engineering Internships
Electronic circuits laboratory, quadcopter PCB design, aviation electronics…

Overview

- CERN Accelerator Complex
  - RF Group
  - Impedance Working Group (IWG)
  - IWG Workflow
- Wakefields and Impedances
- Impedance Study Examples
  - Vertex Locator (LHCb)
  - Beam Gas Ionization Chamber (SPS)
  - Beam Wire Scanner (LHC)
  - Scraper (SPS)
- Summary

The CERN accelerator complex
Complexe des accélérateurs du CERN



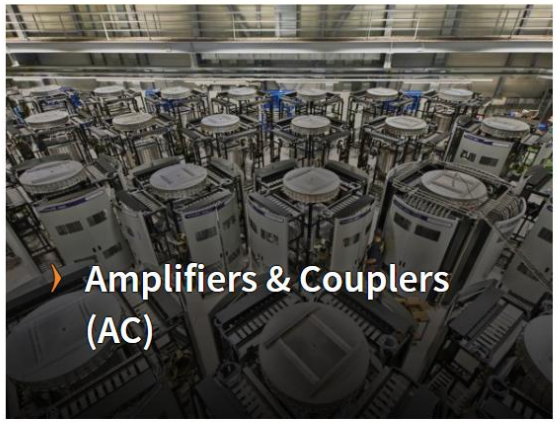
H⁻ (hydrogen anions) · p (protons) · ions · RIBs (Radioactive Ion Beams) · n (neutrons) · p̄ (antiprotons) · e⁻ (electrons) · μ (muons)

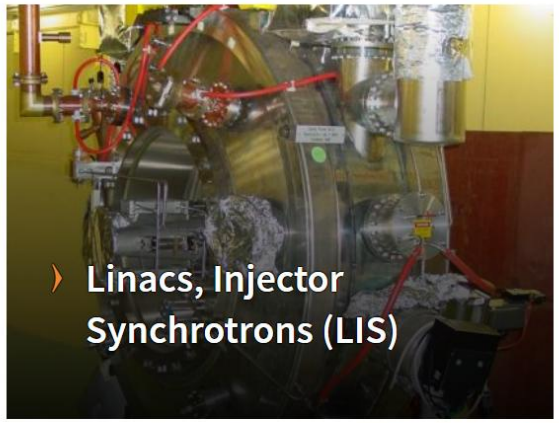
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

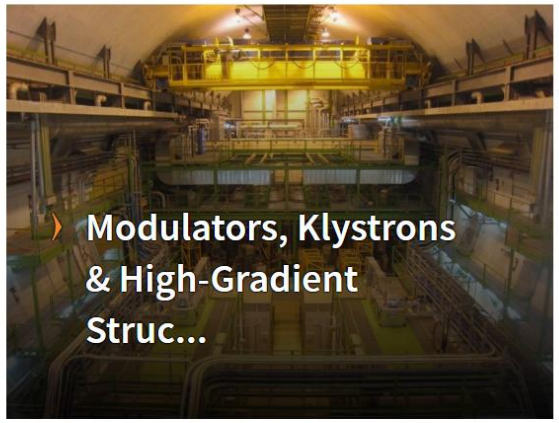
https://cds.cern.ch/record/2800984

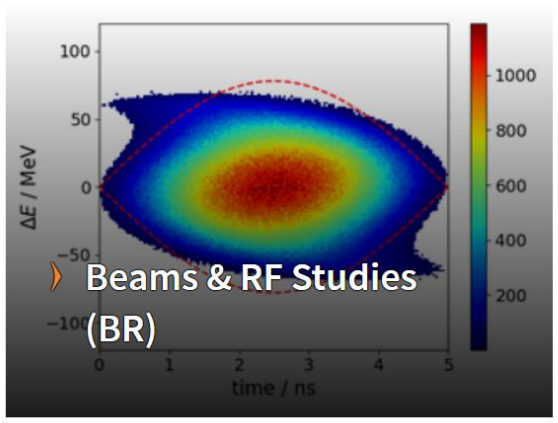
RF Group

SECTIONS



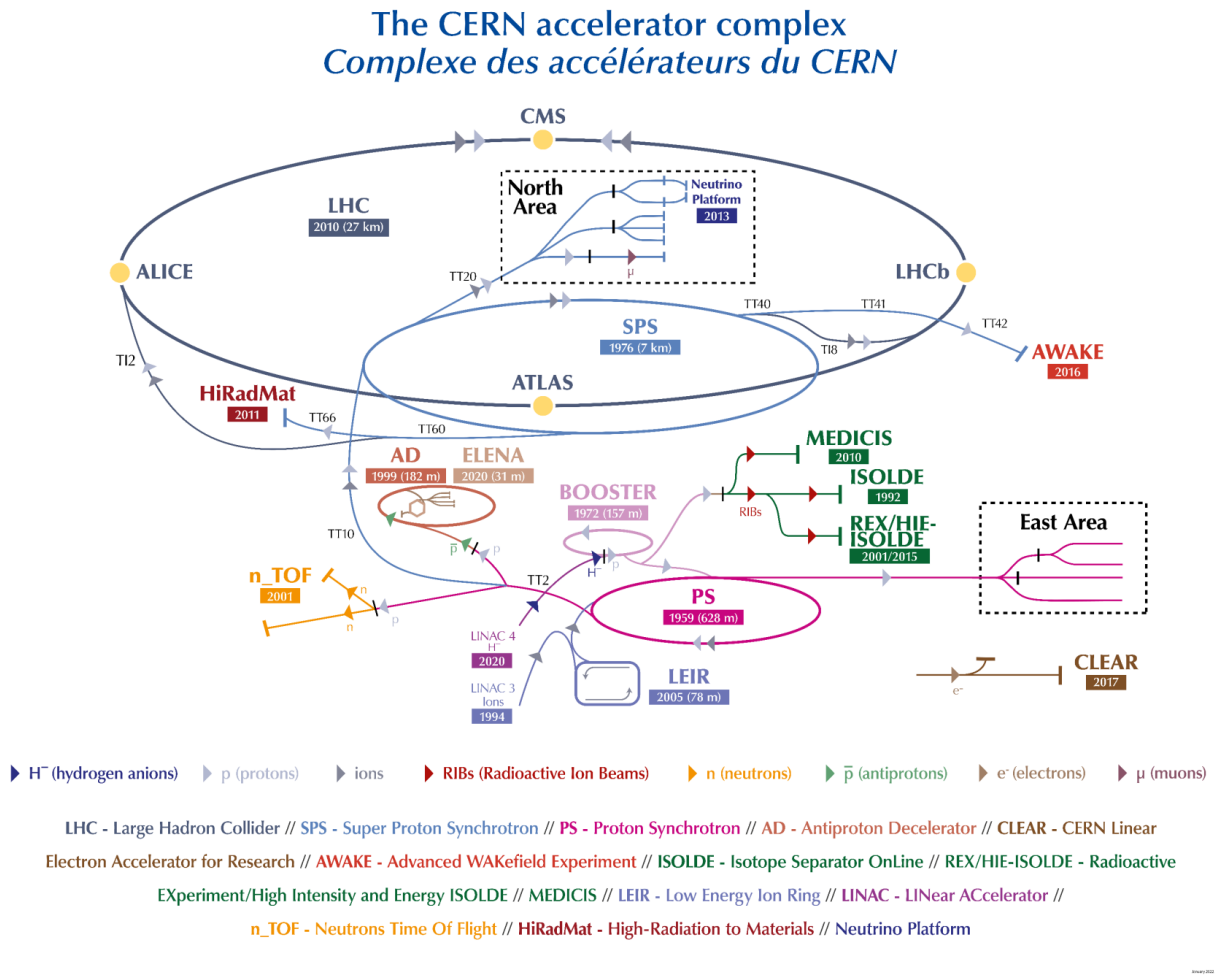






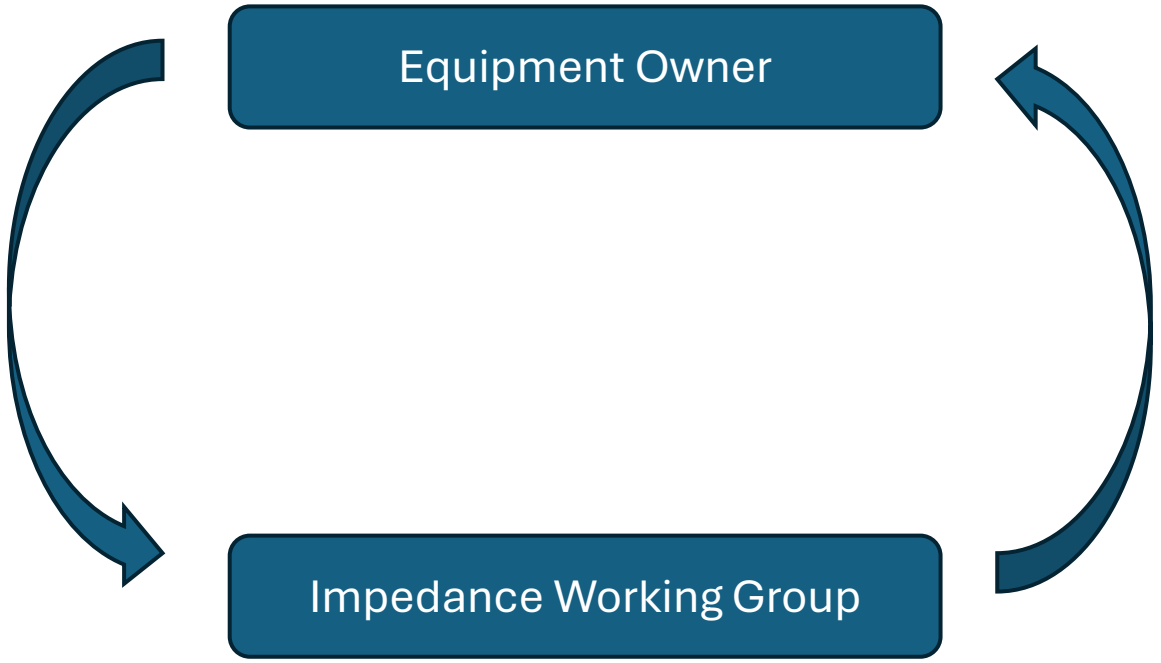
https://sy-dep-rf.web.cern.ch/

Impedance Working Group (IWG)



- IWG is a subgroup of Colleagues from BR and ABP.
- Responsible for the longitudinal and transverse impedance studies of the components to be installed to the rings (PS, SPS, LHC).
- Such as; magnets, bellows, diagnostic elements etc.

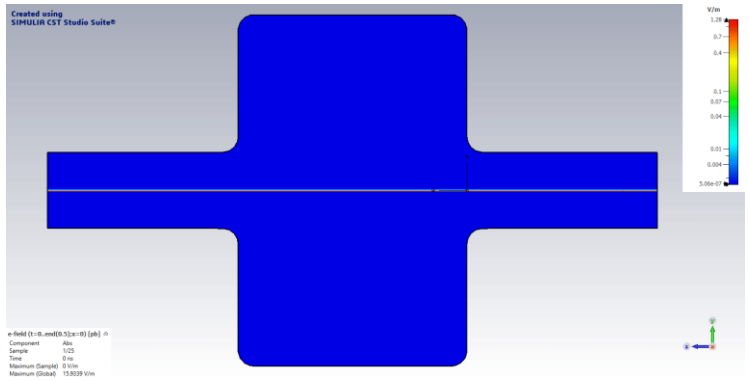
IWG Workflow



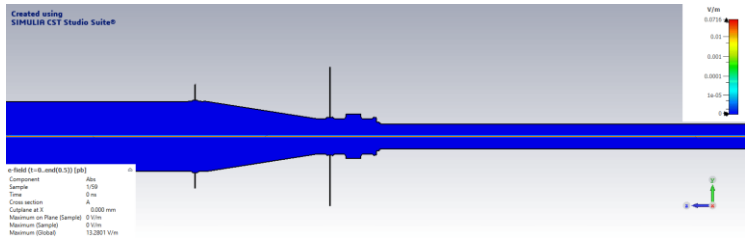
- Equipment owner contacts the IWG.
- First impedance check of the device and simulation study.
- Update meetings between the R&D teams of both groups.
- After completion of the impedance study, devices goes to installation inside the tunnel.

Wakefields and Impedances

Pillbox Cavity

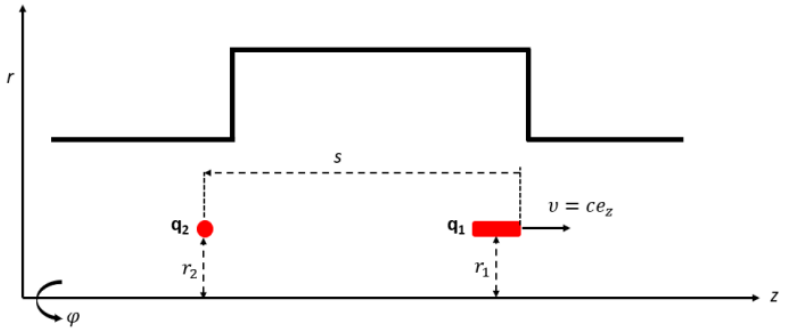


Taper and Bellow



- While particle beam passes through an accelerator component (cavity, bellow etc.), it will induce a voltage.
- The electromagnetic fields (wakefields) will be left inside the component. They perturb the upcoming beam, causing beam instabilities.

A bunch with total q_1 traverse a cavity followed by a test charge q_2



Time Domain -> "Wake Potential"

Fourier Transform

$$\vec{W}(r_1, s) = \frac{1}{q_1} \int_{-\infty}^{+\infty} dz \left[\vec{E}(r_1, z, t) + c\vec{e_z} \times \vec{B}(r_1, z, t)\right]_{t=\frac{s+z}{c}}$$

Frequency Domain -> "Impedance"

$$Z_{||} = \frac{1}{c} \int_{-\infty}^{+\infty} ds\, W_{II}(x, y, s) \exp(-i \frac{\omega}{c} s)$$ [1]

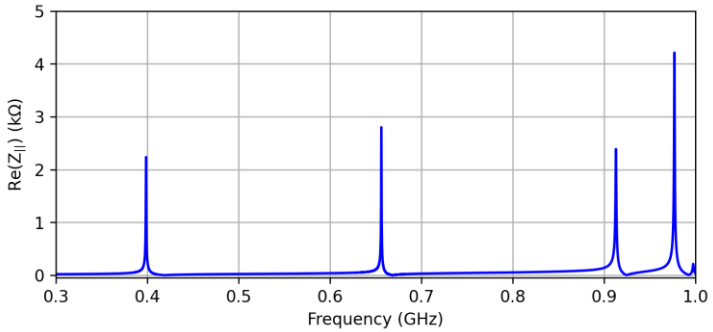
[1] T.Weiland and R. Wanzenberg, Wake fields and impedances, Proc. of the CAT - CERN Accelerator School (CCAS), pp.140-180, 1993

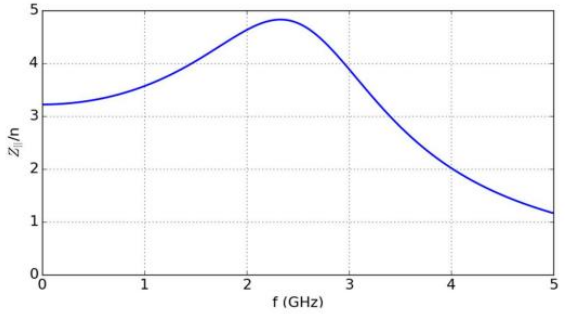
Impedance Types and Effects

Impedance Types

- **Narrowband** $\Delta f \ll \frac{1}{\tau}$
- **Broadband** $\Delta f \gg \frac{1}{\tau}$

$$Q = \frac{f_{res}}{\Delta f}$$





[1]

[2]

Impedance Effects

- *Energy loss* — Beam-induced heating
- *Resonant kicks -> Instabilities* — Beam loss and beam blow-up

[3]

- The impedance response of each machine element must be studied before the installation.
- It is crucial for the stable operation of the accelerator complex.

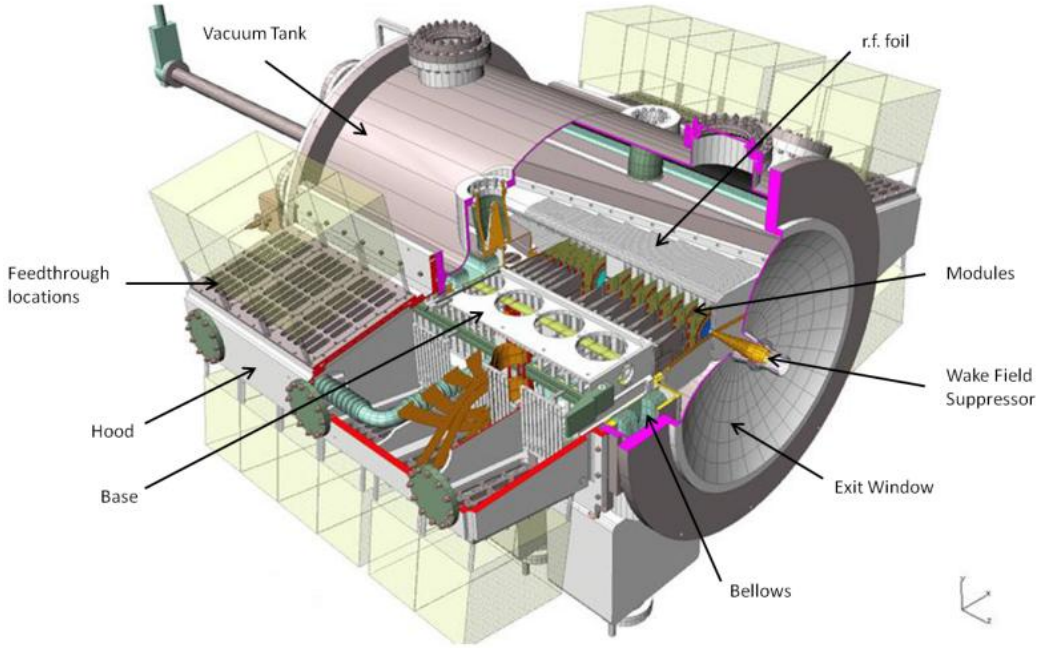
[1] C. Vollinger et al., "Needs and Solutions for Machine Impedance Reduction", Proc. of ICFA Mini-Workshop on Impedances and Beam Instabilities in Particle Accelerators, Benevento, Italy, 2017.
[2] M. Migliorati, "Collective Effects", JUAS 2022 Course 1: The Science of Particle Accelerators, 01.02.2022
[3] Vacuum for Particle Accelerators Impedance Tutorials, S. Calatroni, B. Salvant.

Impedance Study Examples

- Vertex Locator (LHCb)
- Beam Gas Ionization Chambers (SPS)
- Beam Wire Scanners (LHC)
- Scraper (SPS)

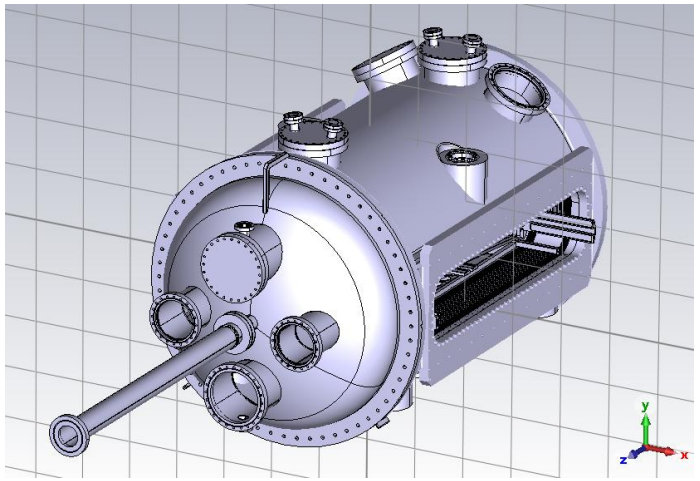
Vertex Locator - VeLo

VeLo Tank and Key Components

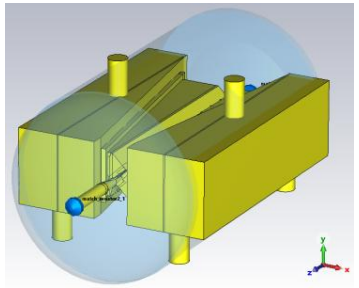


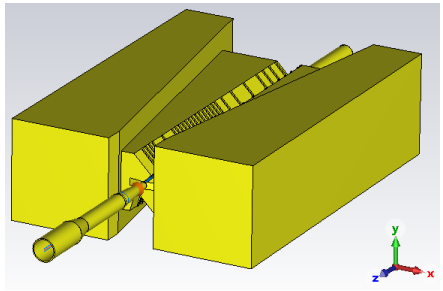
- Silicon sub-detector surrounding the LHCb interaction point ~ 3 mm to colliding LHC beams
- Recreates the traces of the particles from LHC collisions
- Previous work (*measurement & simulation of longitudinal impedance, heating localization analysis*) was done by B. K. Popovic

VeLo CAD Model



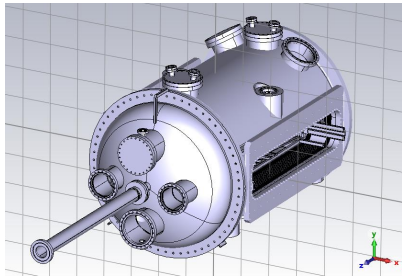
CST Models
(Frequency domain and Wakefield solvers)



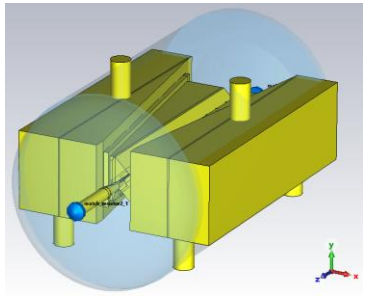


Vertex Locator - VeLo

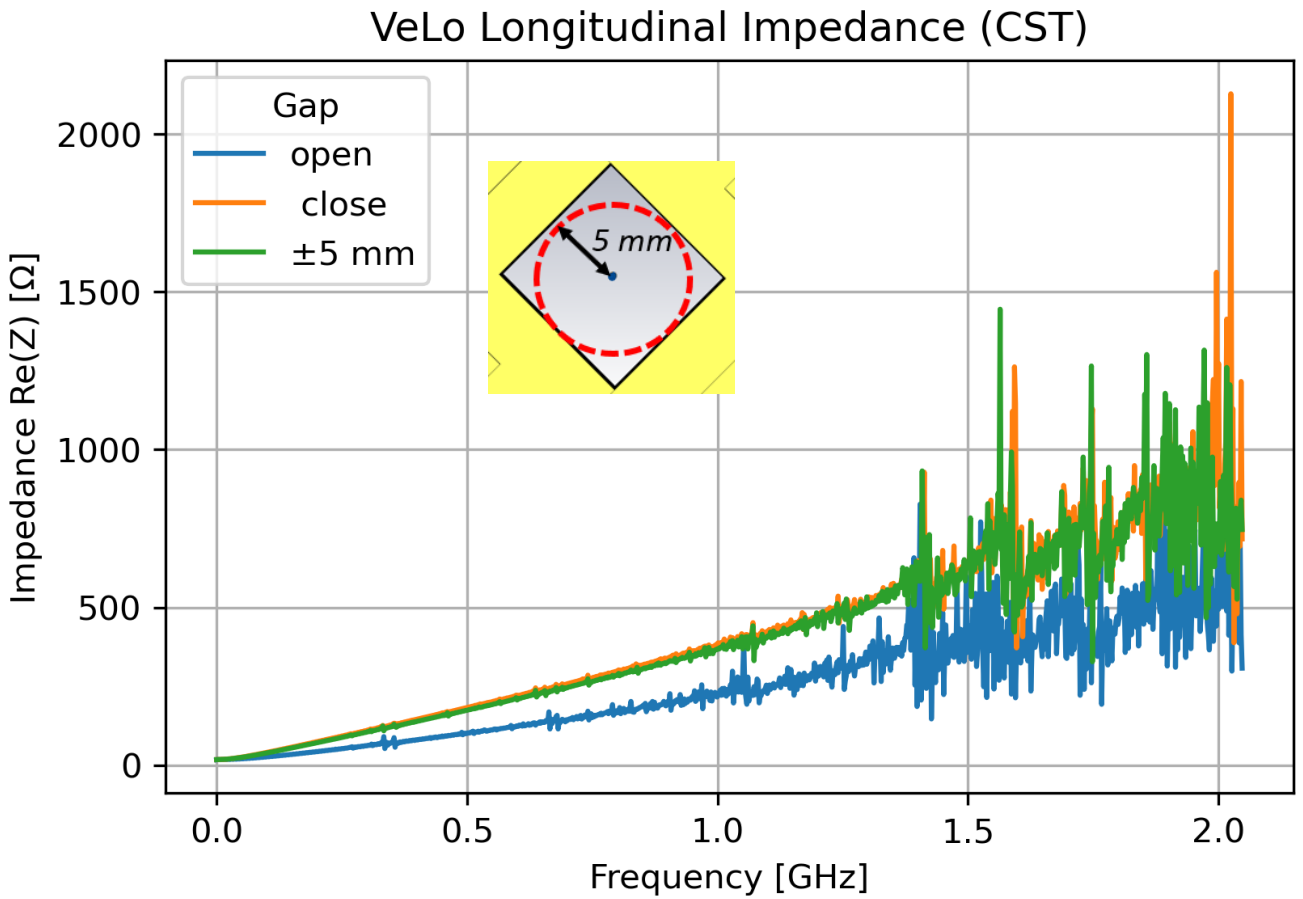
CAD Model



CST Model



- Simulation model and mesh settings were kept the same for consistency.
- Simulation on server
  243 h 1 m 25 s ~ 10 days
- Green curve -> ±5 mm gap.
  No visible change!
- Additional modifications can be implemented on the model.



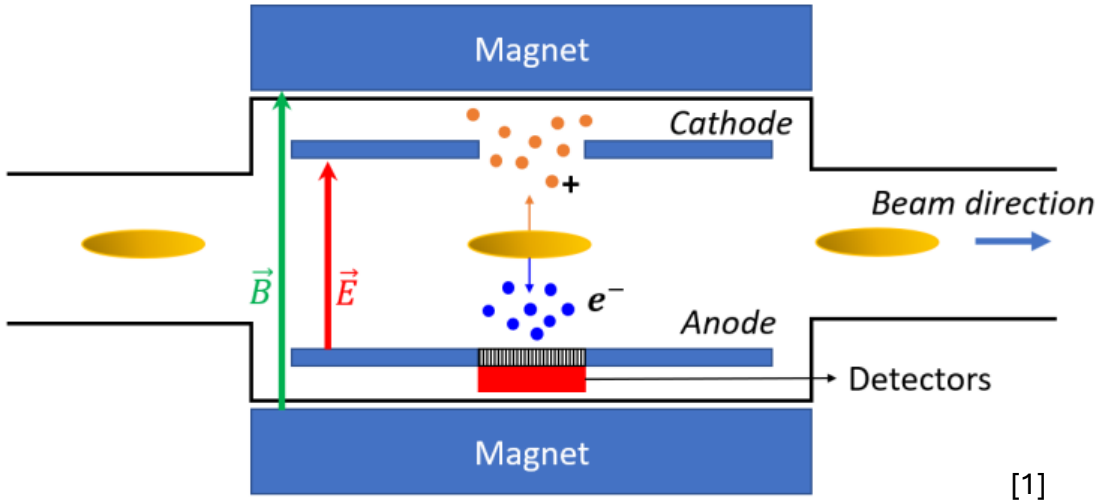
Impedance Study Examples

- Vertex Locator (LHCb)
- Beam Gas Ionization Chambers (SPS)
- Beam Wire Scanners (LHC)
- Scraper (SPS)

Beam Gas Ionization (BGI) Monitors

- Non-destructive transverse beam profile monitors.
- Complex device -> high voltage, compact design, detector readout, cooling channels.
- Two identical BGIs in the SPS ring, one horizontal and one vertical installation to get the beam profile information in both planes.
- Installation during year end technical stop (YETS) 2023/24.
  - Horizontal model (installed).
  - Vertical model (upcoming technical stop).

Working Principle



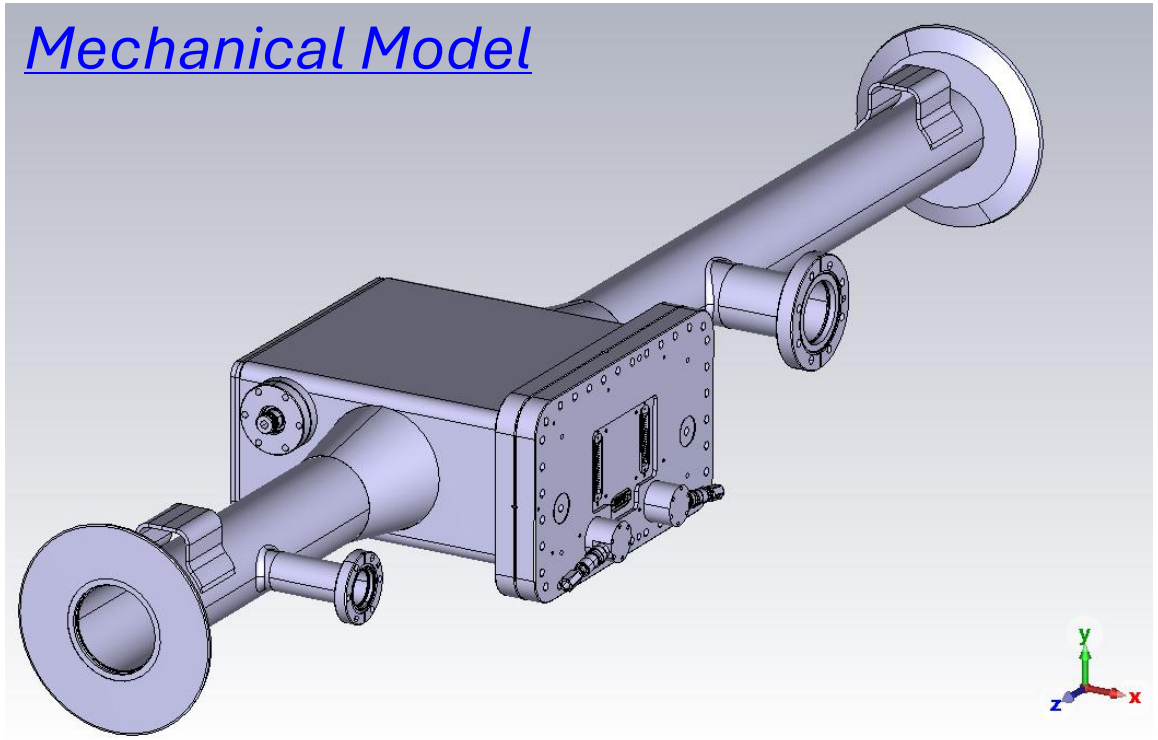
[1]

1) The beam ionizes the residual gas in the instrument.
2) The ionization image of the electrons are obtained through the detectors by the applied external magnetic and electric fields.

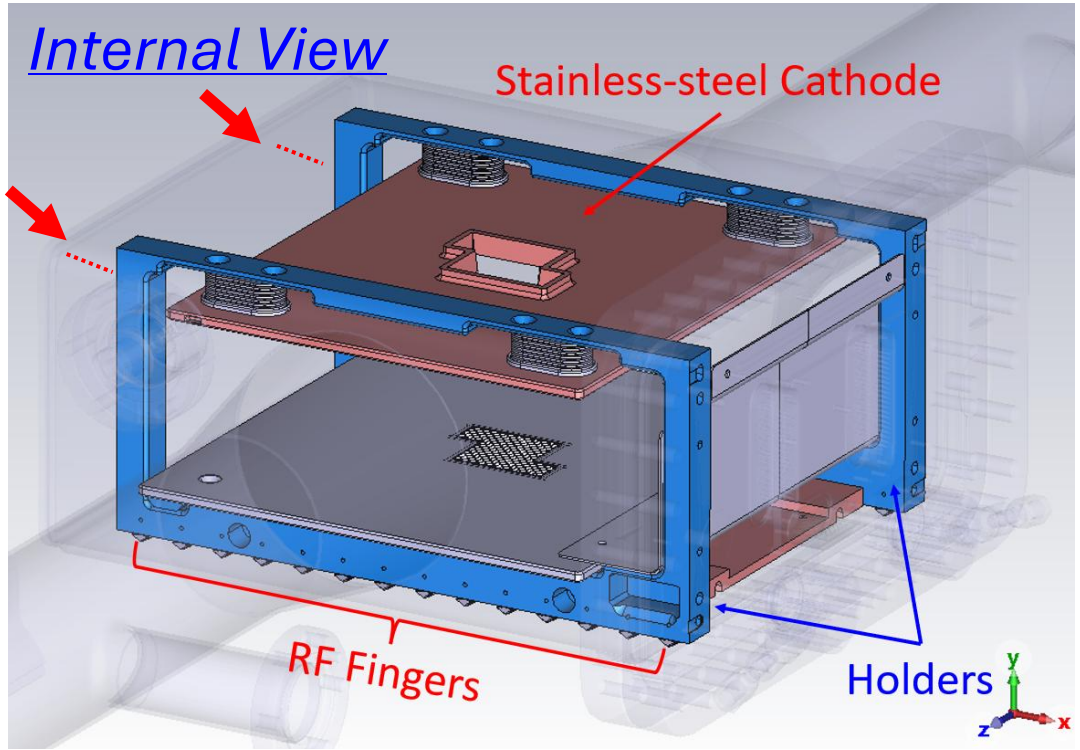
[1] S. Levasseur, "Development of a Hybrid Pixel Detector Based Transverse Profile Monitor for the CERN Proton Synchrotron", PhD. thesis, Phys. Dept., Royal Halloway University of London, London, UK, 2019.

Initial Design

Mechanical Model



Internal View

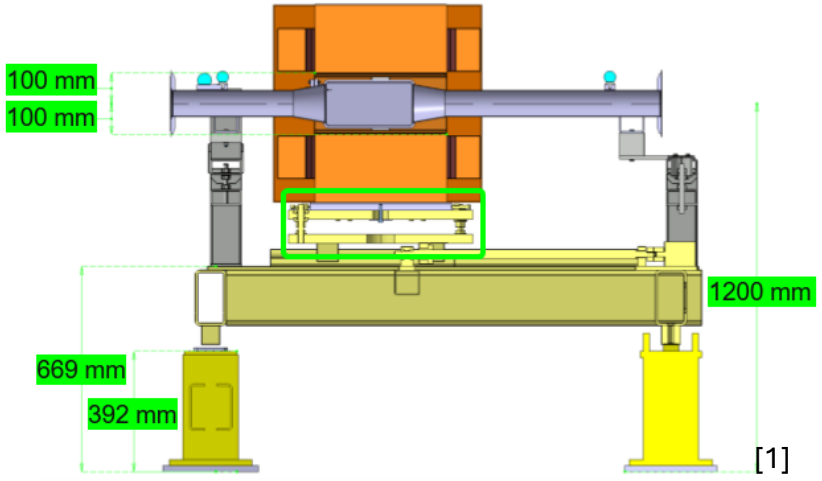


First look

- RF fingers are placed only at the bottom part.
- The instrument holders at the back part are not in contact with the vacuum chamber.

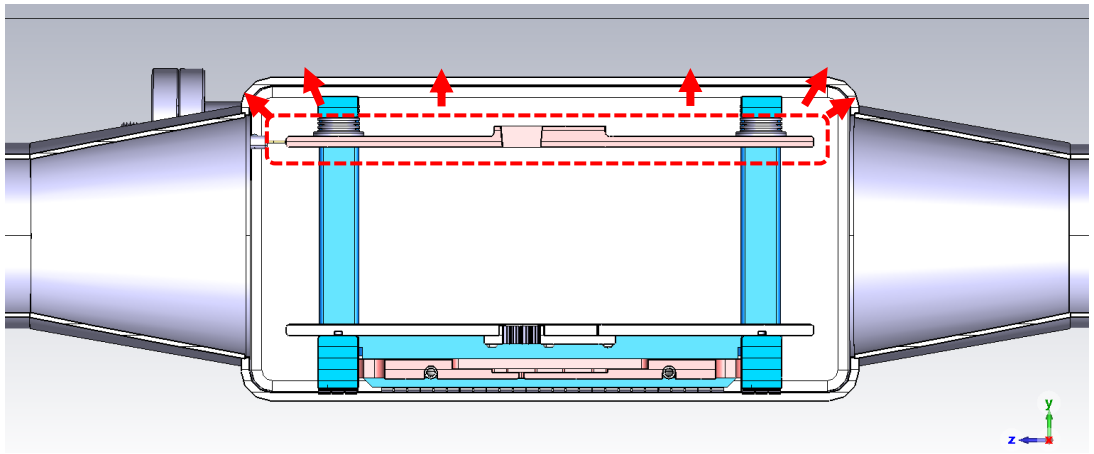
Constraints on Model

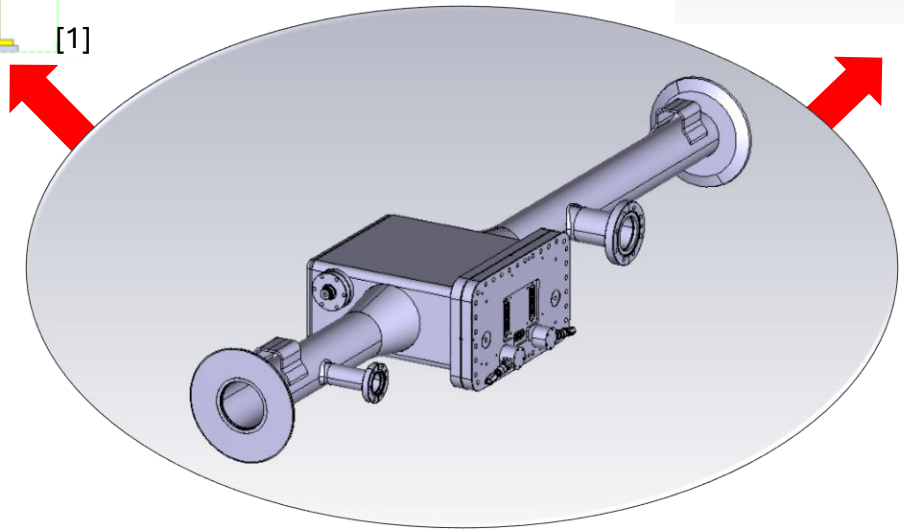
BGI inside Magnet



[1]

BGI Initial Design - Cross-sectional View





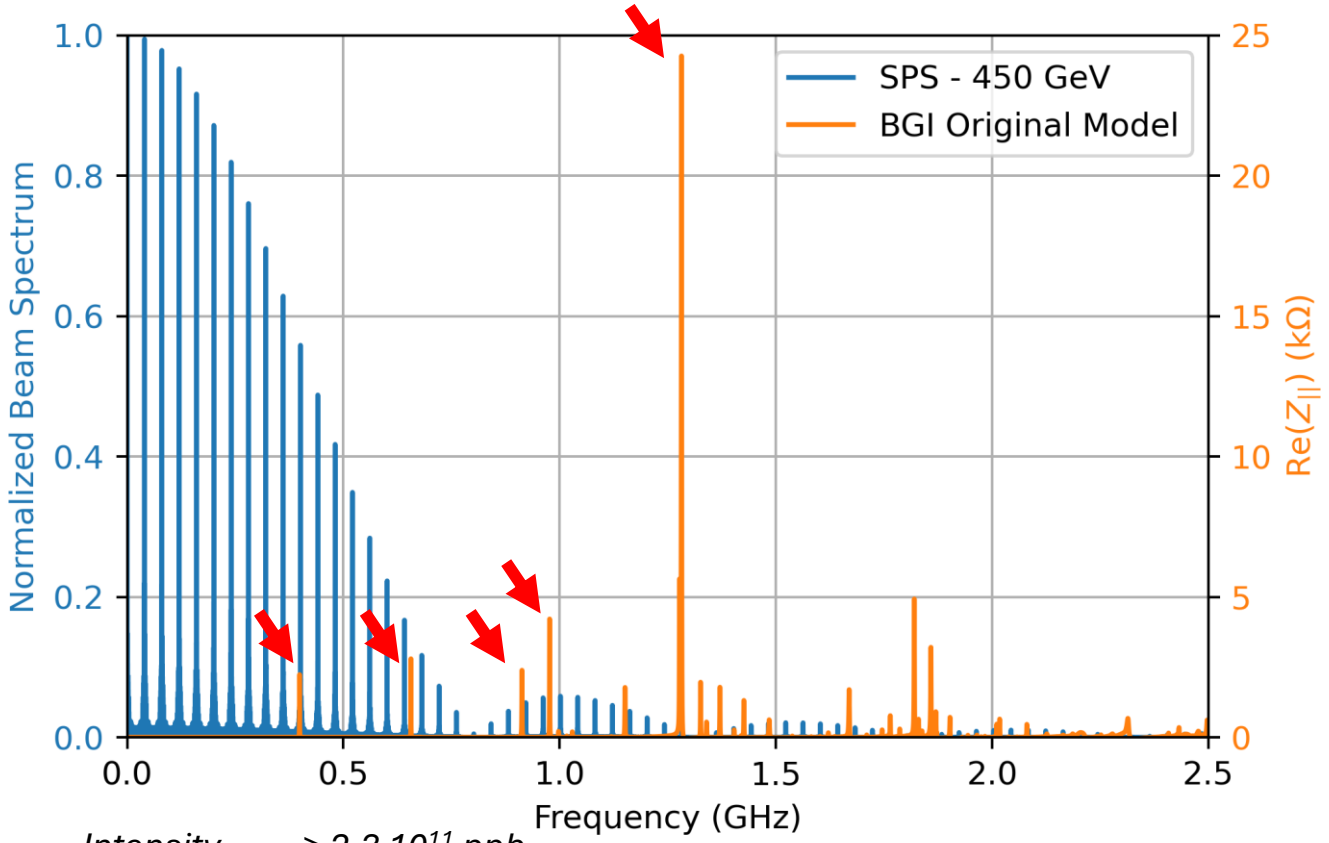
- Placed in an existing dipole magnet.
- Limited space.
- No place for HOM couplers.

- High DC voltage **-30 kV** on cathode.
- Spacing required to prevent possible sparking.

[1] T. Ramos, "SPS-BGI Review Meeting", https://indico.cern.ch/event/1273318/ , 03.04.2023

Preliminary Result (1)

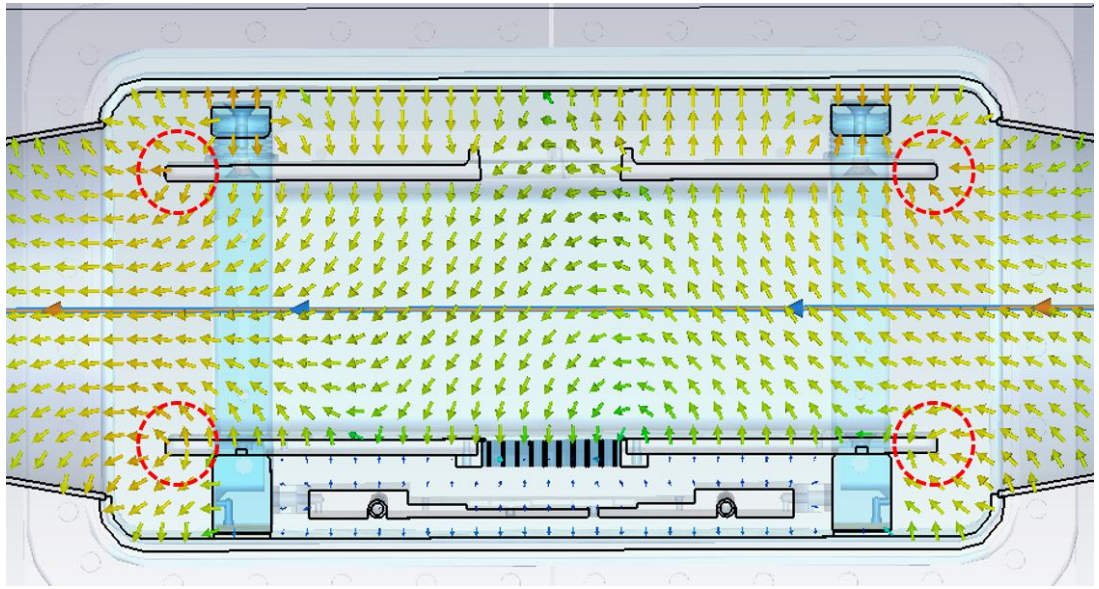
- CST Particle Studio Wakefield Solver [1]
- Many resonances were detected in the simulated relevant beam spectrum up to 2.5 GHz.
- The biggest resonance peak is at 1.28 GHz around 24 kΩ.
- Other peaks:
  - 399 MHz (close to the 10th beam harmonic)
  - 656 MHz
  - 913 MHz
  - 977 MHz



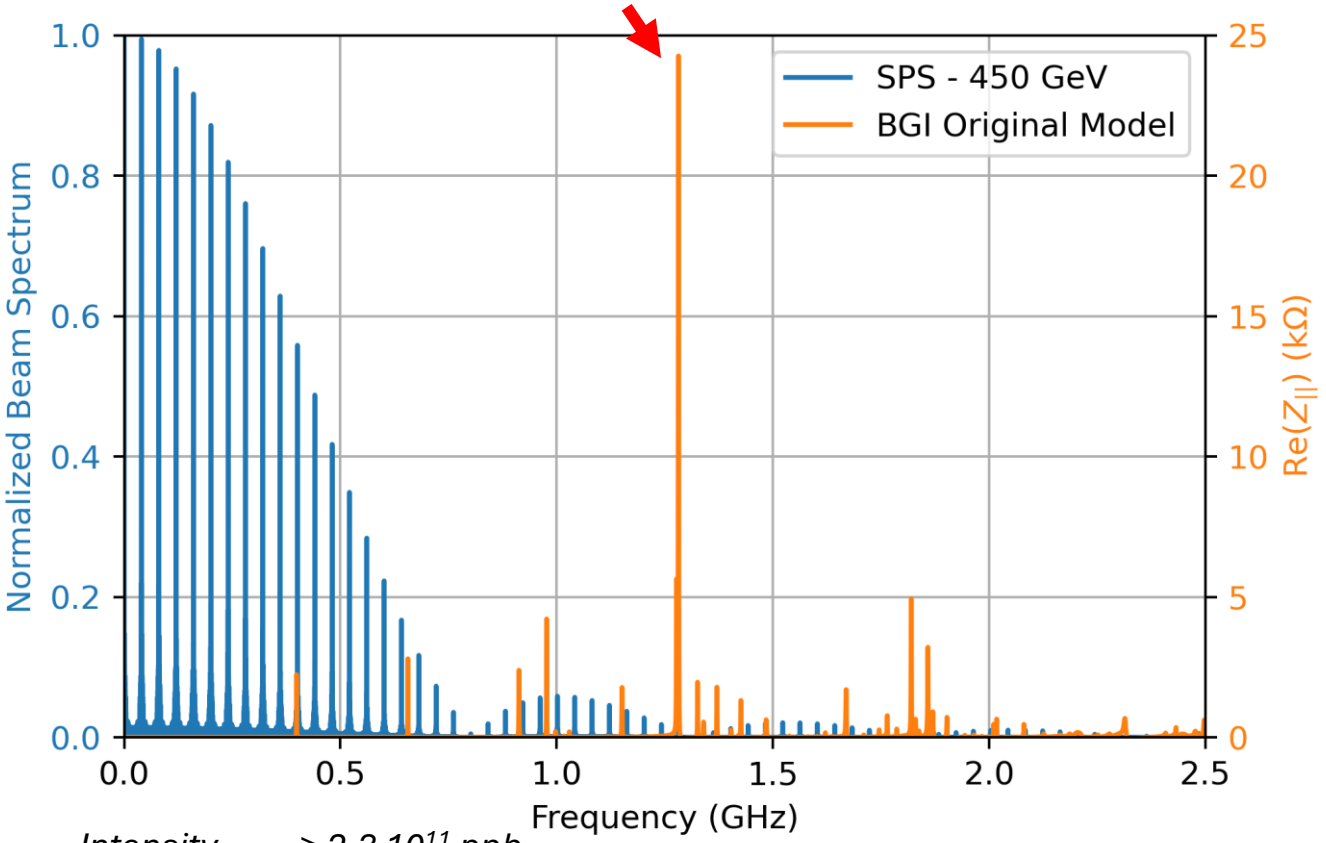
Intensity -> 2.3 10^{11} ppb
Bunch length -> $4\sigma = 1.65\ ns$
Beam spectrum was plotted by BLonD.

[1] CST Studio Suite, https://www.3ds.com/products/simulia/cst-studio-suite

Preliminary Result (2)



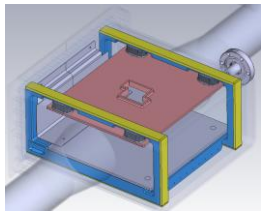
- The source of the resonance peak at 1.28 GHz was identified as the protruding parts of the cathode.



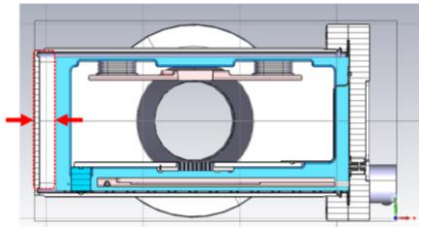
Intensity -> 2.3 10^{11} ppb
Bunch length -> $4\sigma = 1.65\ ns$
Beam spectrum was plotted by BLonD.

Geometrical Modifications

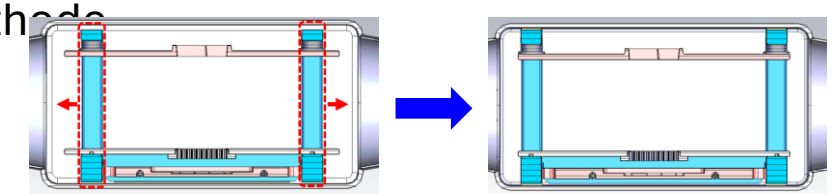
- The holders are fully covered by RF fingers.



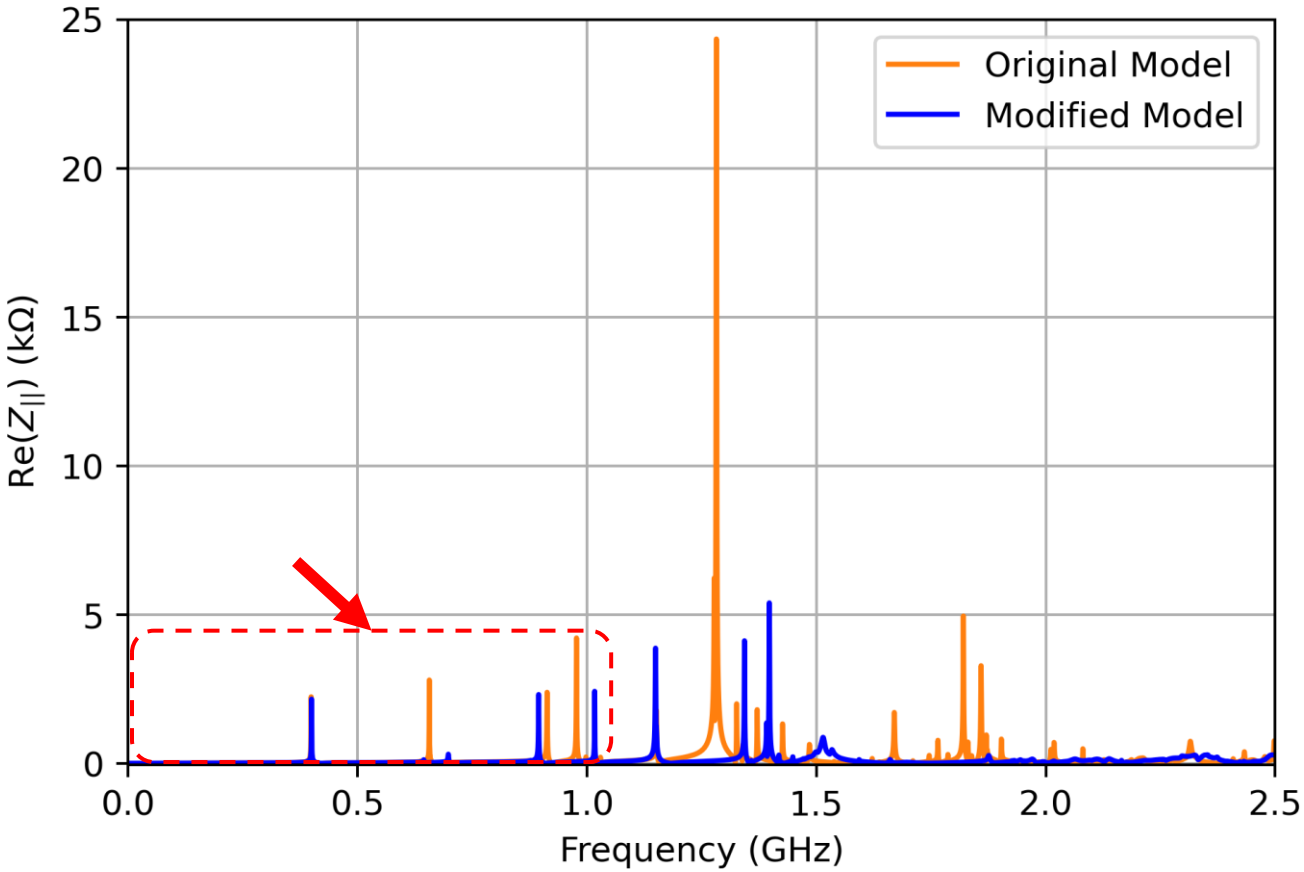
- The chamber was shortened to contact the back part of the holders.



- The holders were moved to cover the protruding parts of the cathode.

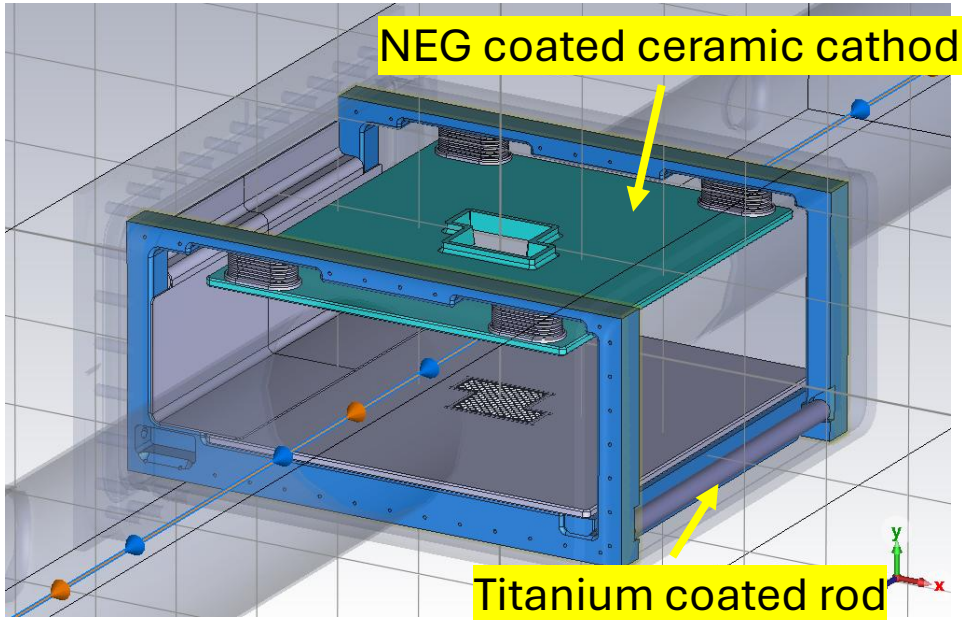


- The tapered beampipes were modified to straight beampipes.



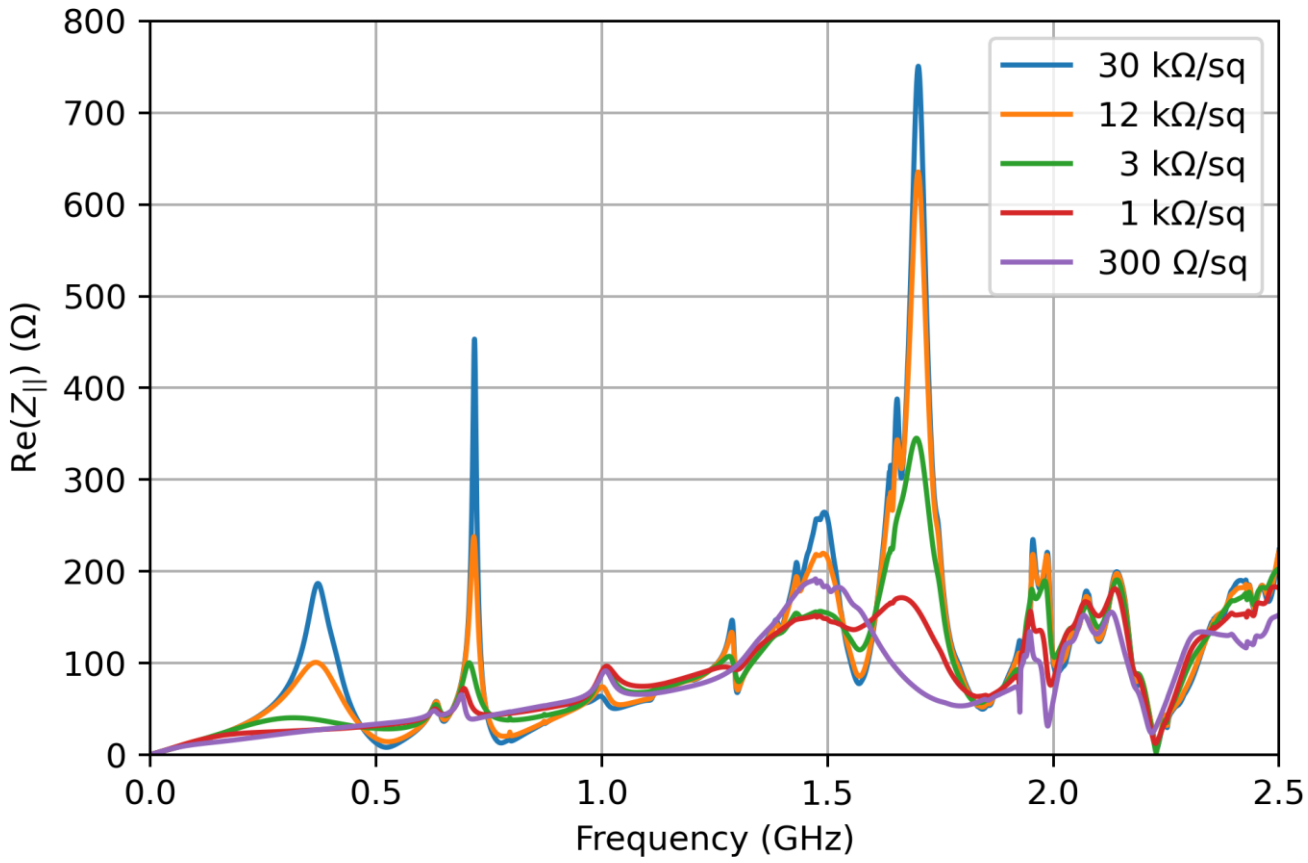
- There are still resonances below 1 GHz.
- Possible solution -> Coatings

Coating Study



- Non-evaporable Getter (NEG) coating on ceramic (Macor) cathode -> Different Resistivities.
- NEG coating -> 1 kΩ was selected.
- Titanium coated ceramic (Alumina) rod -> 10 Ω.

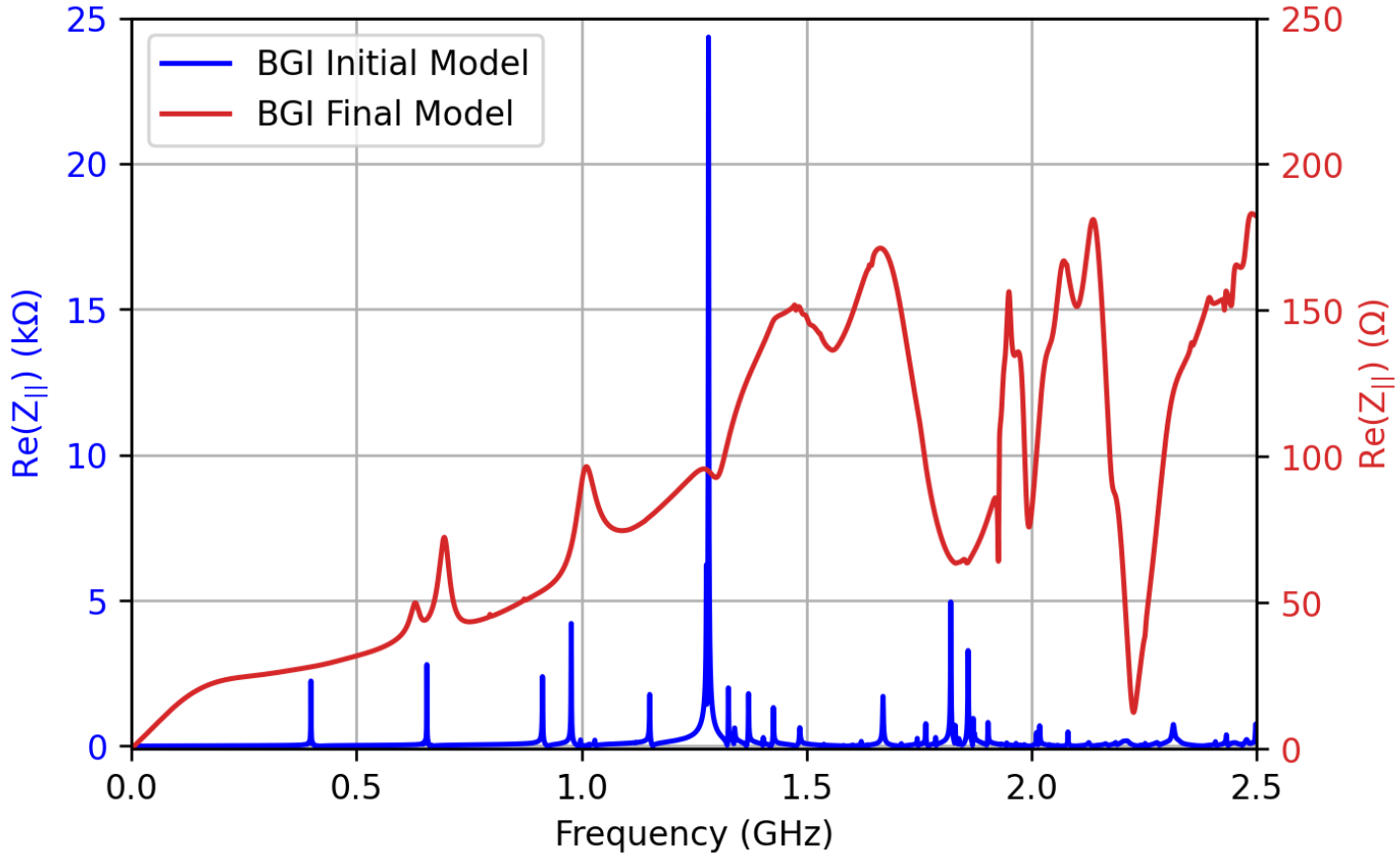
BGI longitudinal impedances with NEG coated cathodes for different resistivities and a damping rod



F. Caspers, "Experience with UHV-compatible microwave absorbing materials at CERN", in Proc. Workshop on Microwave-absorbing Materials for Accelerators (MAMAs), Newport News, VA, USA, Feb. 1993.

Initial and Final Design

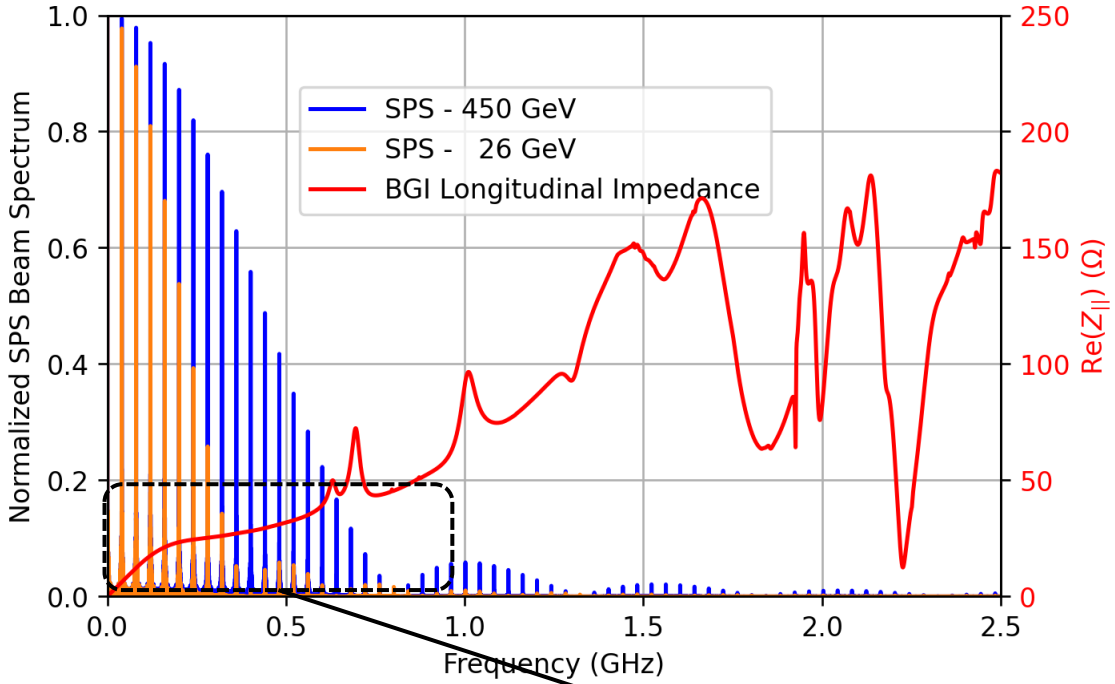
BGI Longitudinal Impedance Initial and Final Model



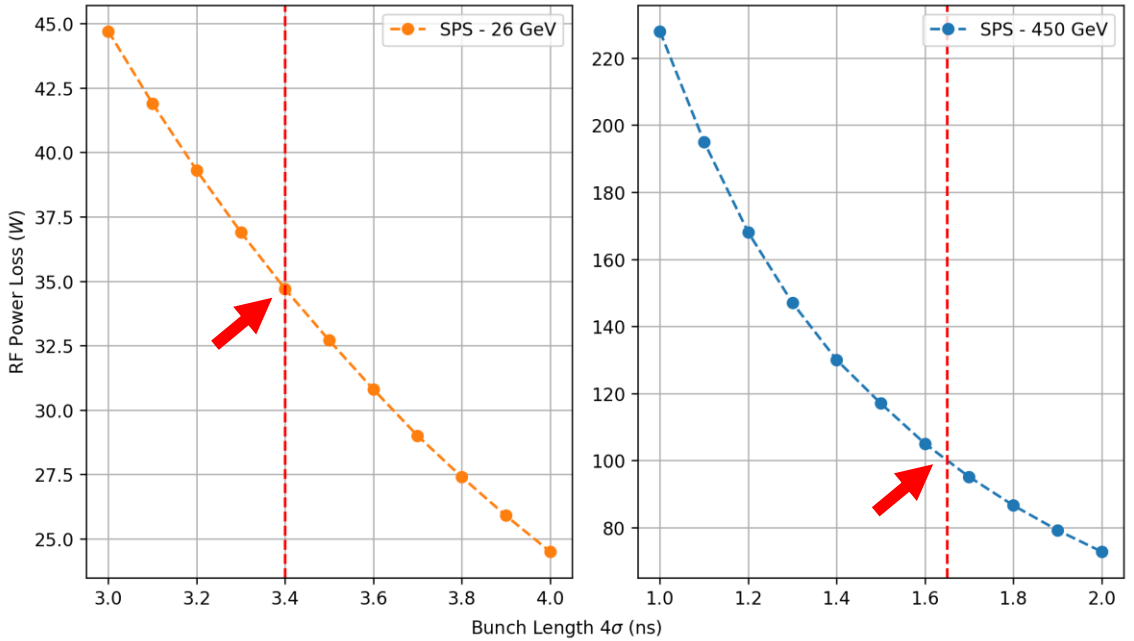
- The geometrical modifications and coatings applied to the initial BGI design.
- The cathode coating showed significant effect on impedance reduction overall studied beam spectrum up to 2.5 GHz.

Beam-induced RF Power Loss

SPS Beam Spectra and BGI Impedance



Beam-induced RF Power Loss



Bunch lengths -> 26 GeV ($4\sigma = 3.4\ ns$) and 450 GeV ($4\sigma = 1.65\ ns$)

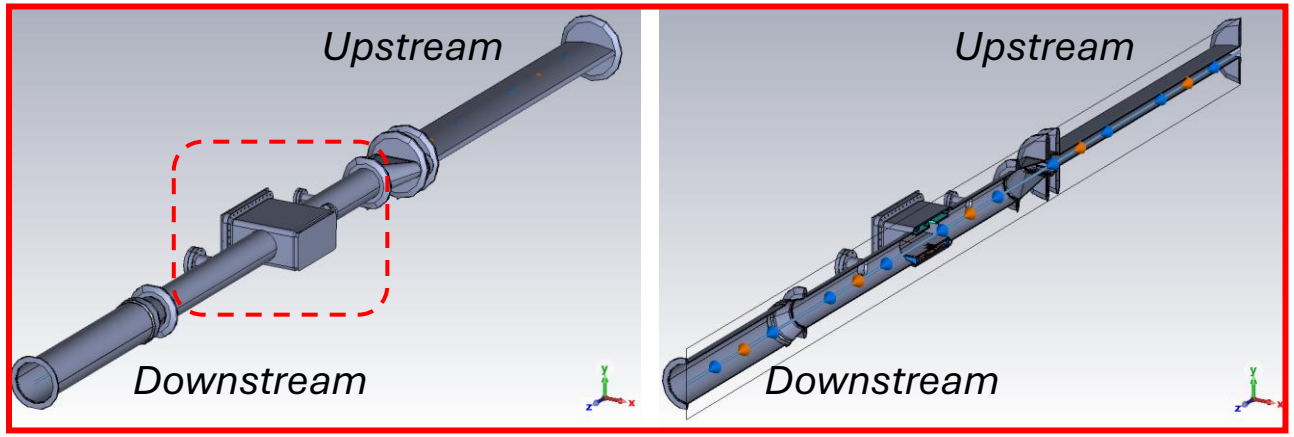
$$P_{loss} = \sum_{p=-\infty}^{\infty} Re[Z_{||}(p\omega_o)]\,|\tilde{I}(p\omega_o)|^2$$

Beam spectrum was plotted by BLonD.
Power loss was computed by BLonD.

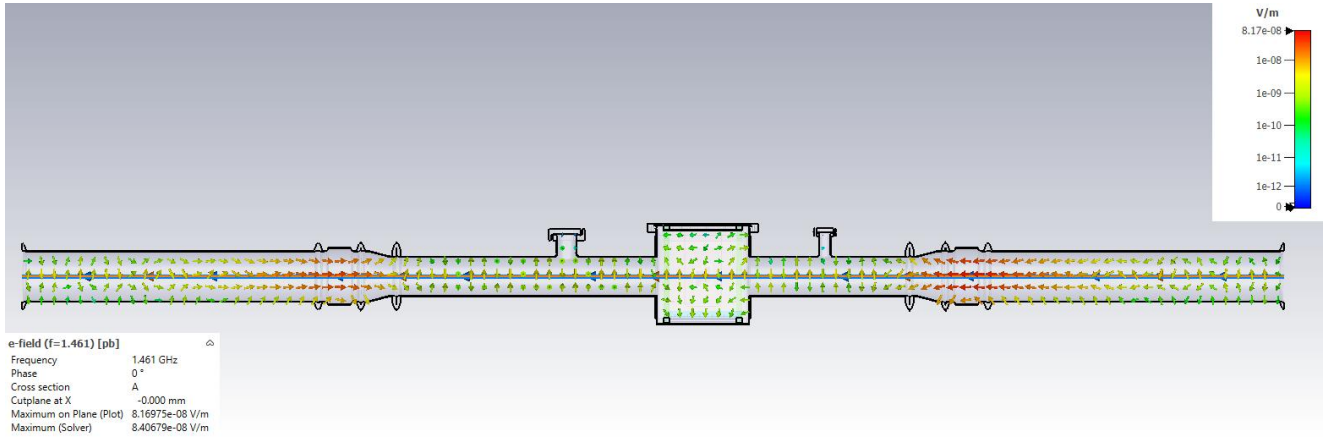
Broadband impedance contribution below 1 GHz.

Integration Models in SPS Ring

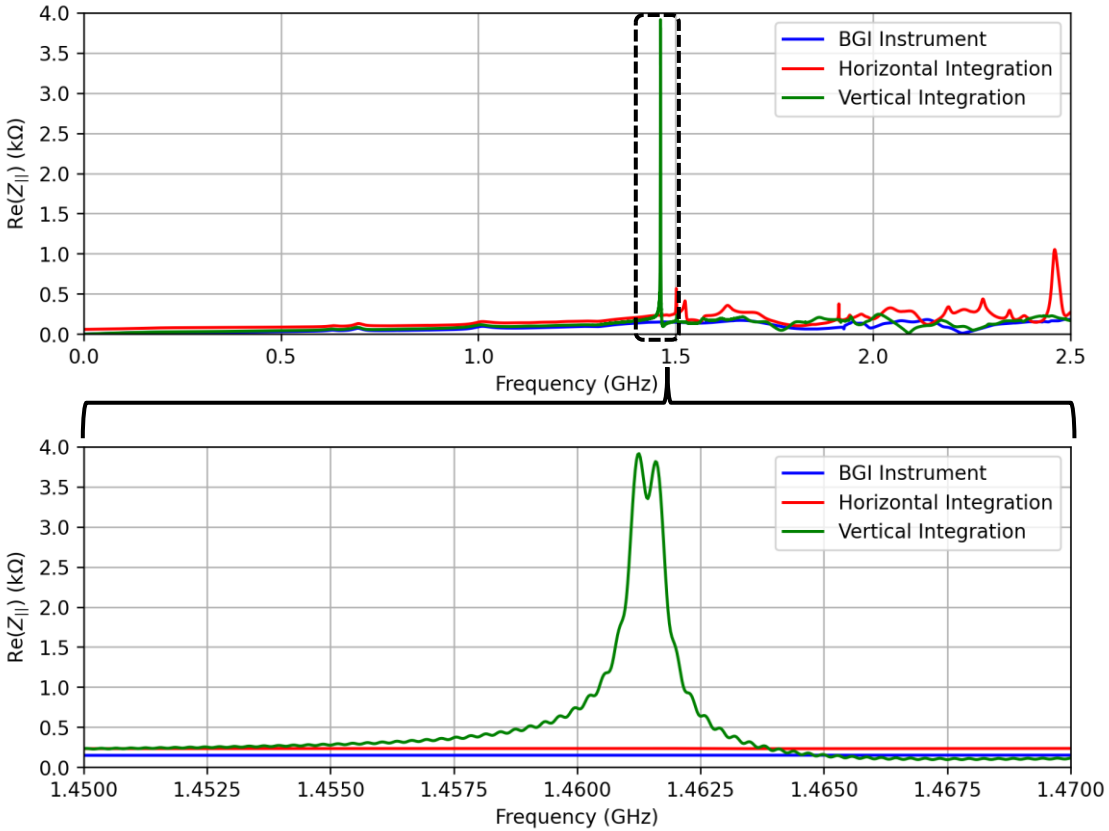
Horizontal Integration



Vertical Integration



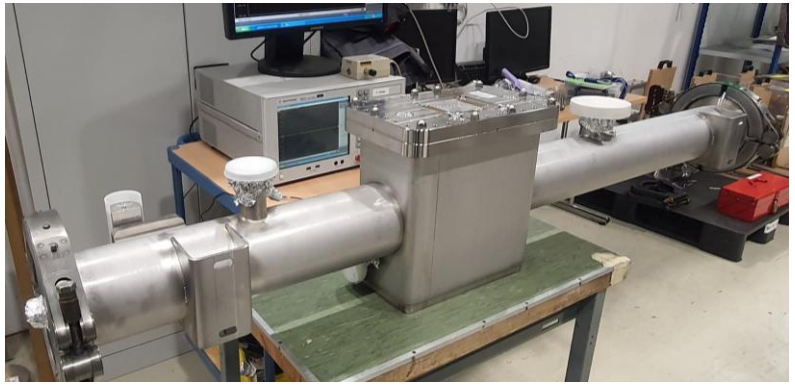
BGI Longitudinal Impedance and Integration Impedances



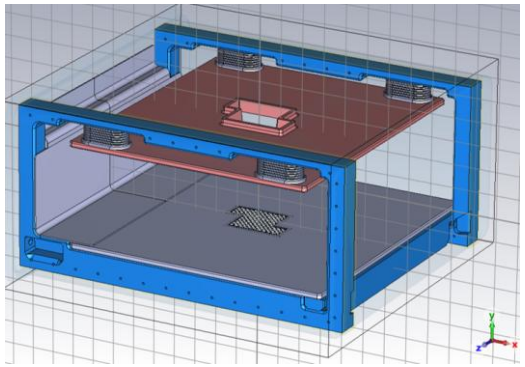
- Resonance peak at ~1.46 GHz with ~4 kΩ magnitude on the vertical integration model.

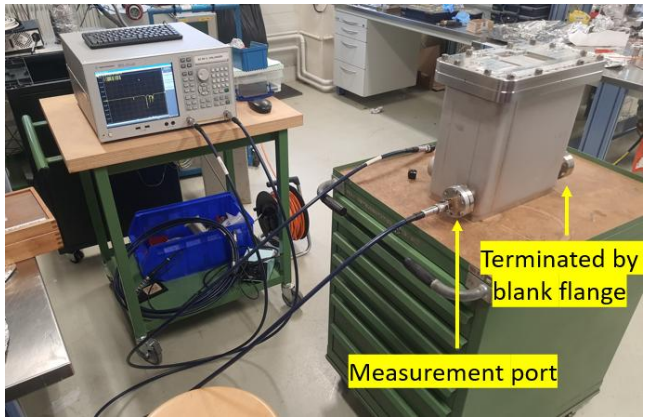
RF Measurements of BGI

Manufactured BGI

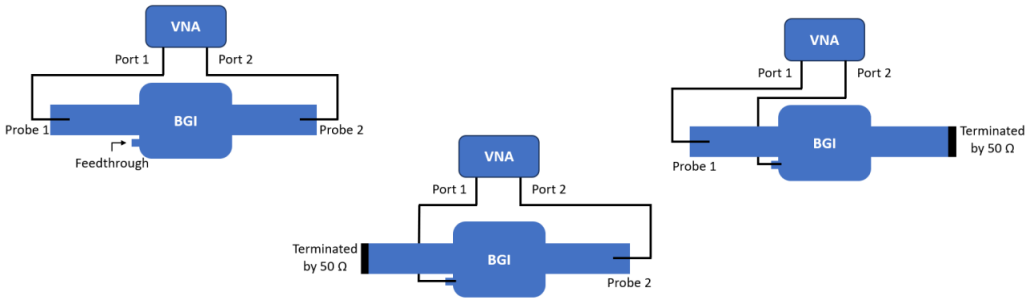


CST Eigen model





- Non-uniform resistivity on the NEG coated cathode (600 Ω on bottom, 1.8 kΩ on top).
- 3 different configurations.
- No cavity resonances were detected.



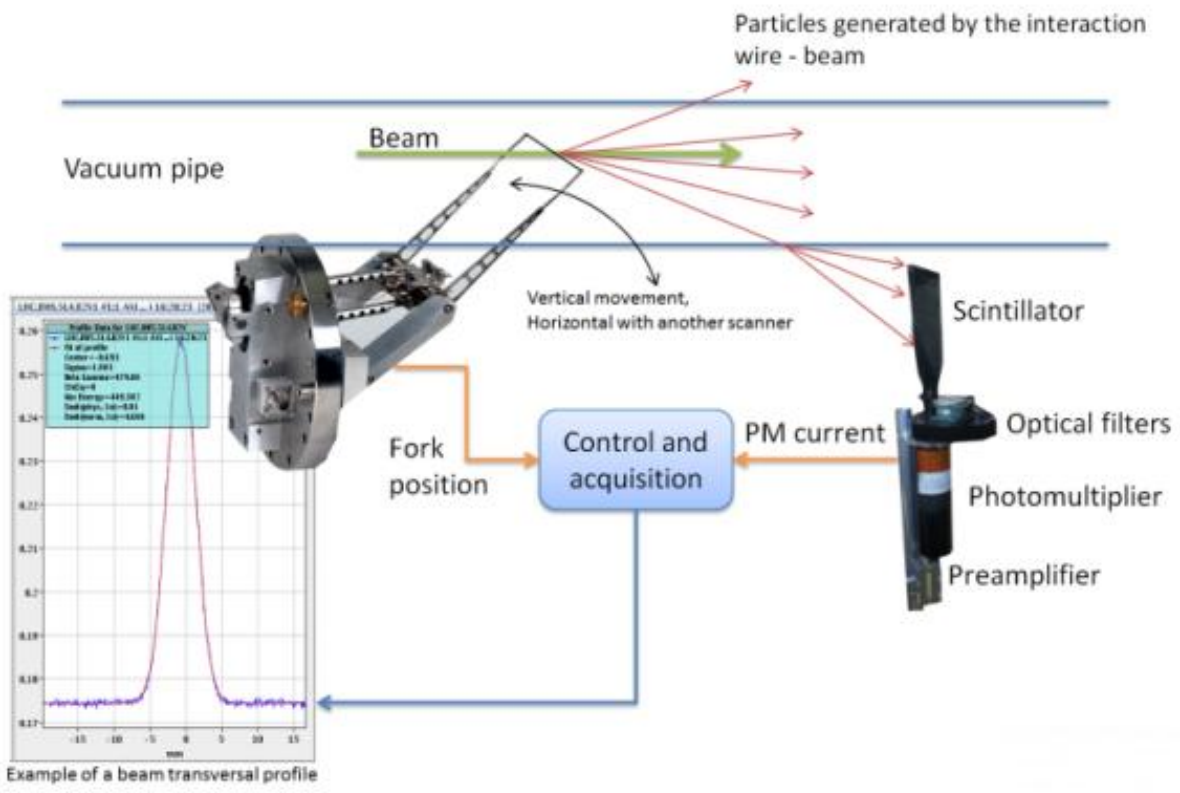
- Signal leakage on the flange! -> Covered by conductive tape.
- Assumed weak coupling.
- Many probe modes were observed as expected.
- Detected modes were confirmed with field patterns in the eigenmode simulation.

f_{sim} (GHz)	0.717	1.11	1.308	2.327	2.355
f_{test} (GHz)	0.714	1.09	1.312	2.328	2.352

Impedance Study Examples

- Vertex Locator (LHCb)
- Beam Gas Ionization Chambers (SPS)
- Beam Wire Scanners (LHC)
- Scraper (SPS)

Beam Wire Scanner



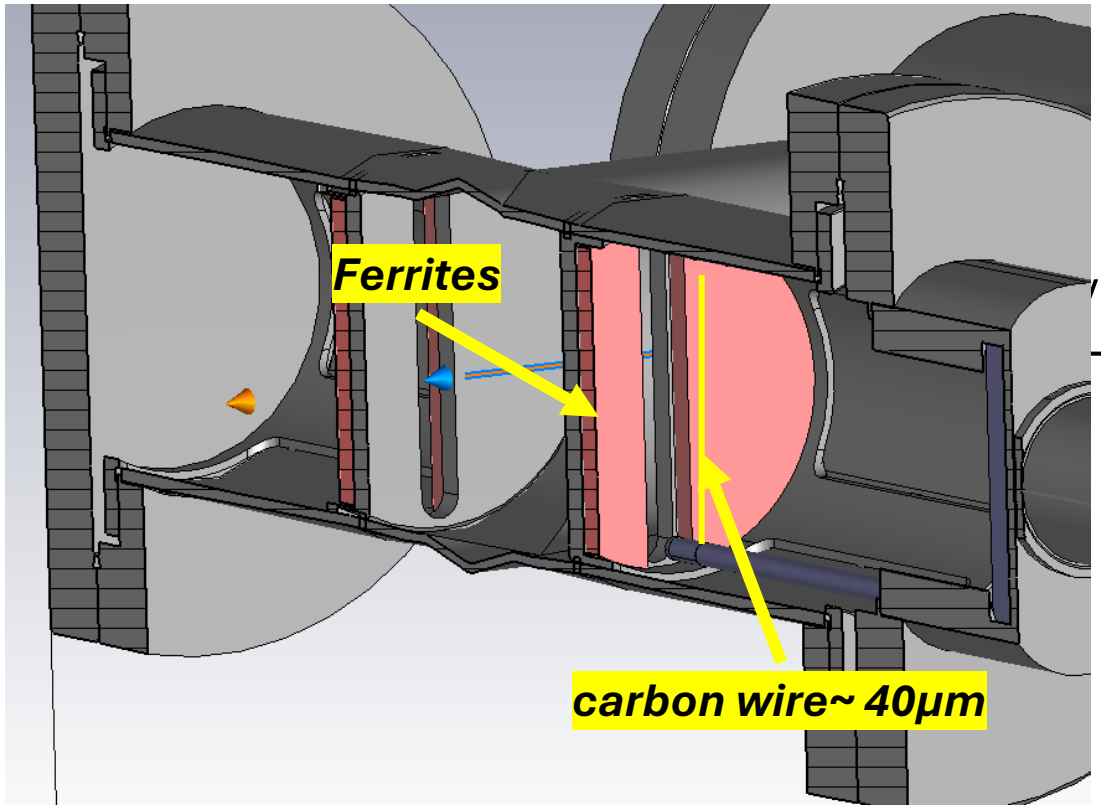
Example of a beam transversal profile

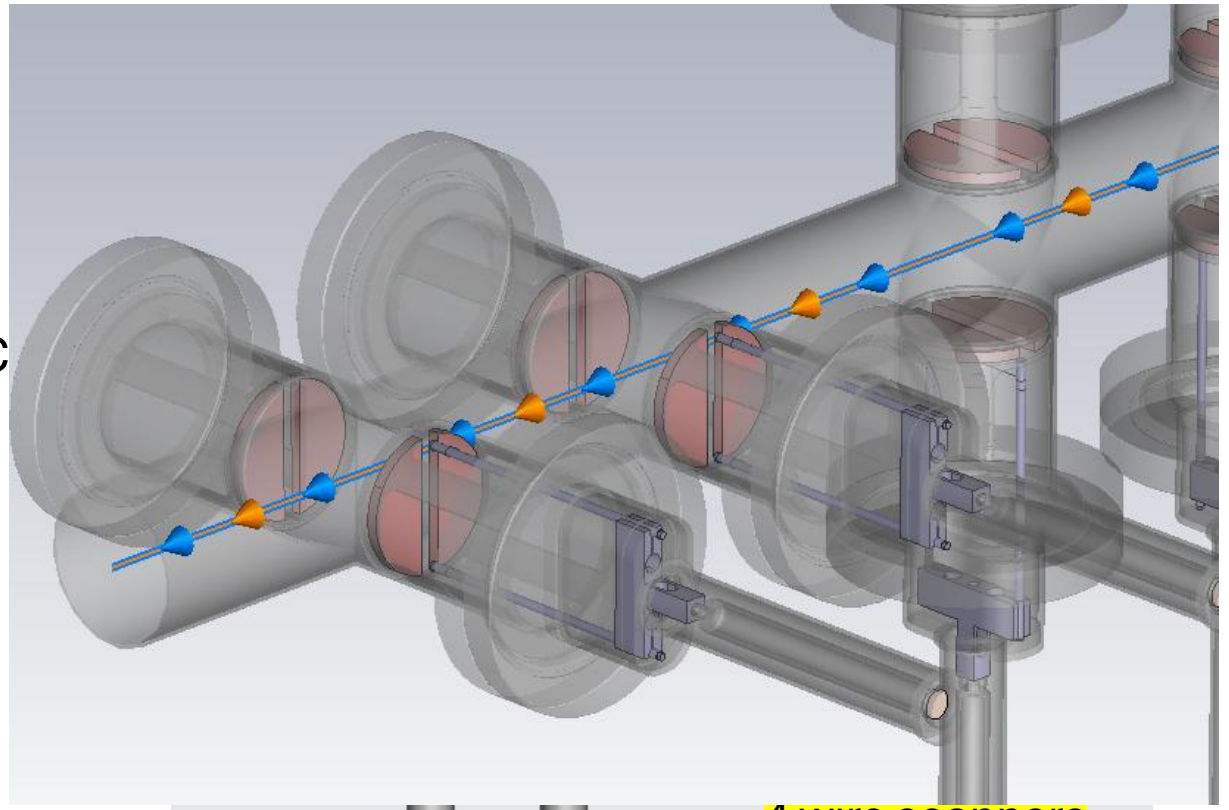
- Diagnostic element used to measure the **transverse profile** (size and shape) of a particle beam.
- Working principal is based on the secondary particles generated from the interaction of the beam and the moving carbon wire.
- The intensity of the generated signal is proportional to the local beam intensity at the wire's position.
- By recording the signal as a function of wire position, the beam intensity distribution is obtained.

[*]

** B. Dehning, J. Emery, J. Herranz Alvarez, M. Koujili, J. L. Sirvent Blasco, "Vacuum Actuator and Controller Design for a Fast Wire Scanner", 2012 Beam Instrumentation Workshop, Newport News, VA, USA, 15 - 19 Apr 2012, pp.195-197*

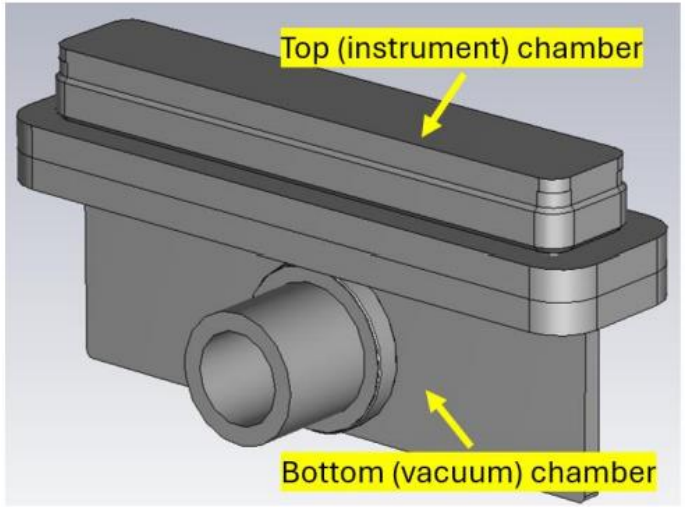
Beam Wire Scanner – Legacy Model

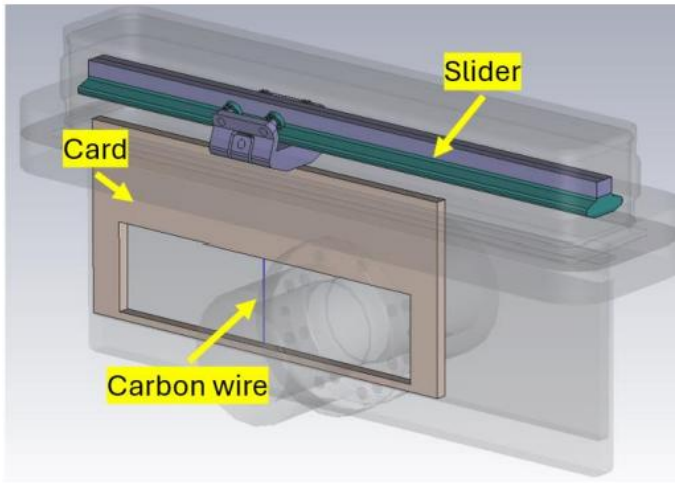


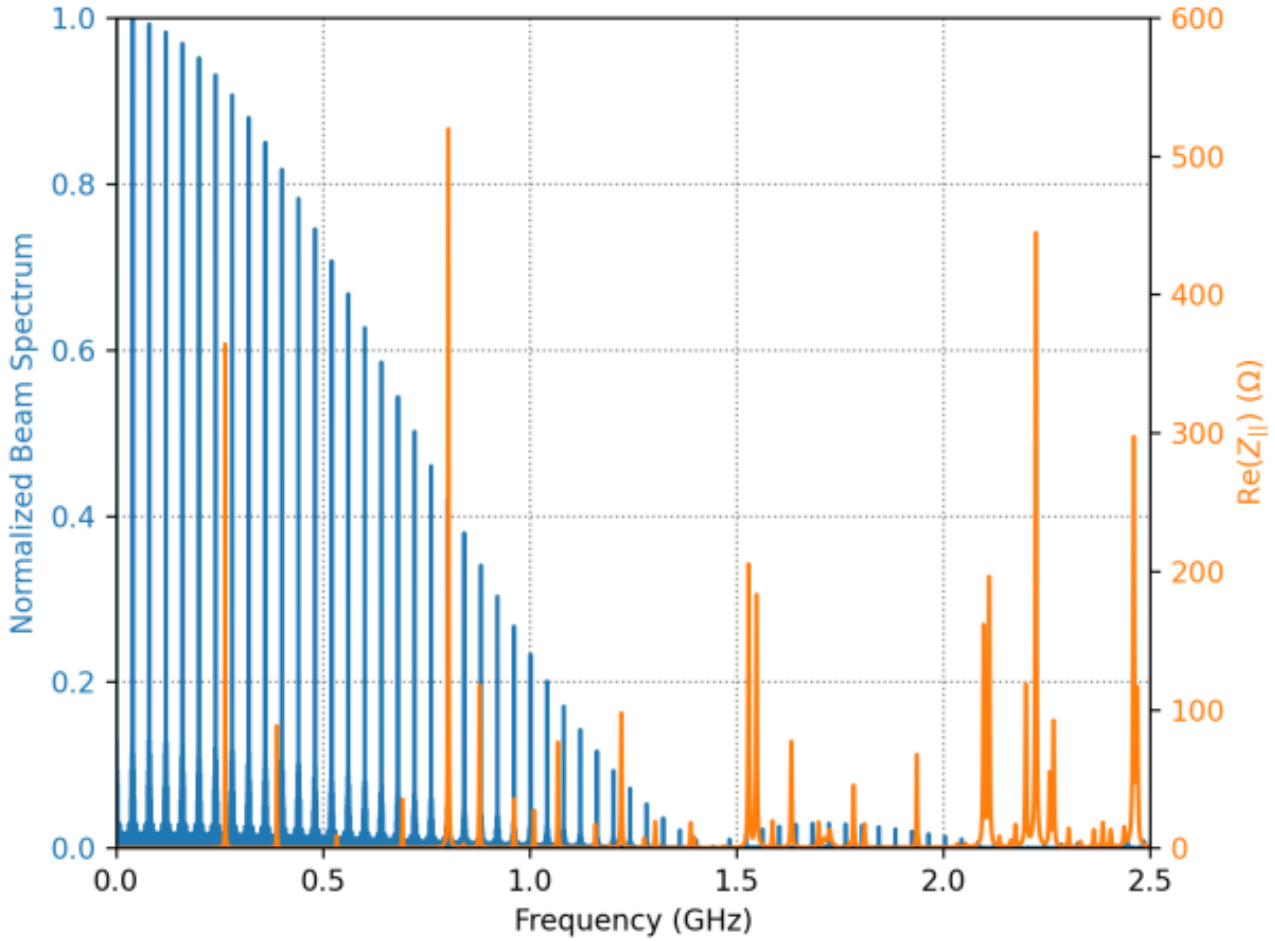


4 wire scanners

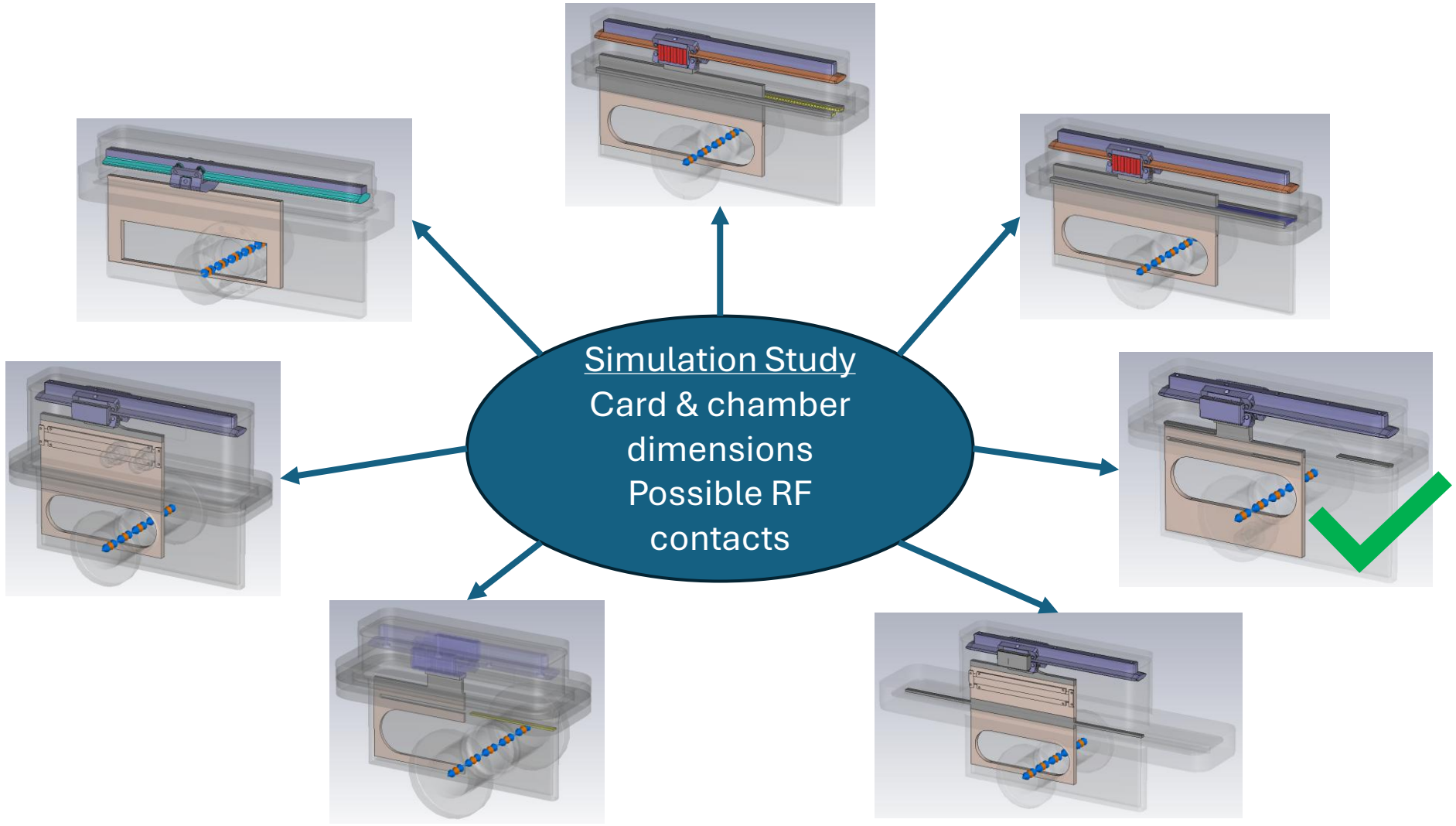
Beam Wire Scanner - Initial Model



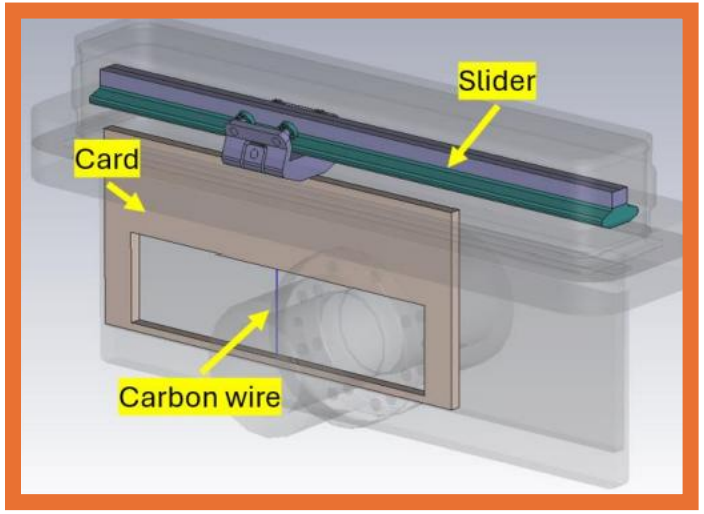


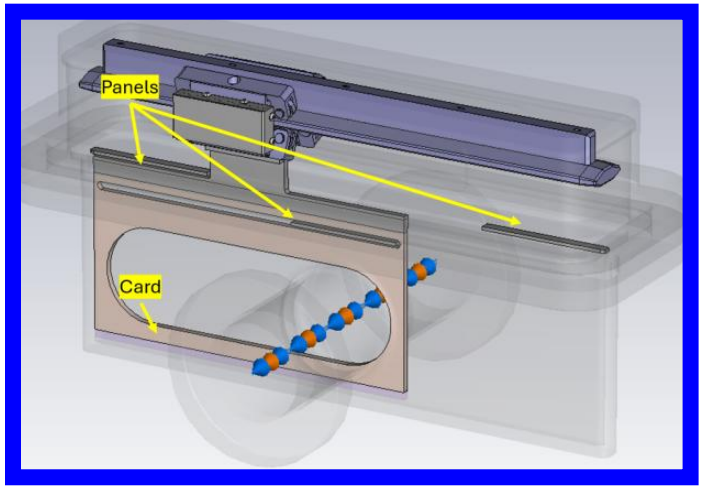


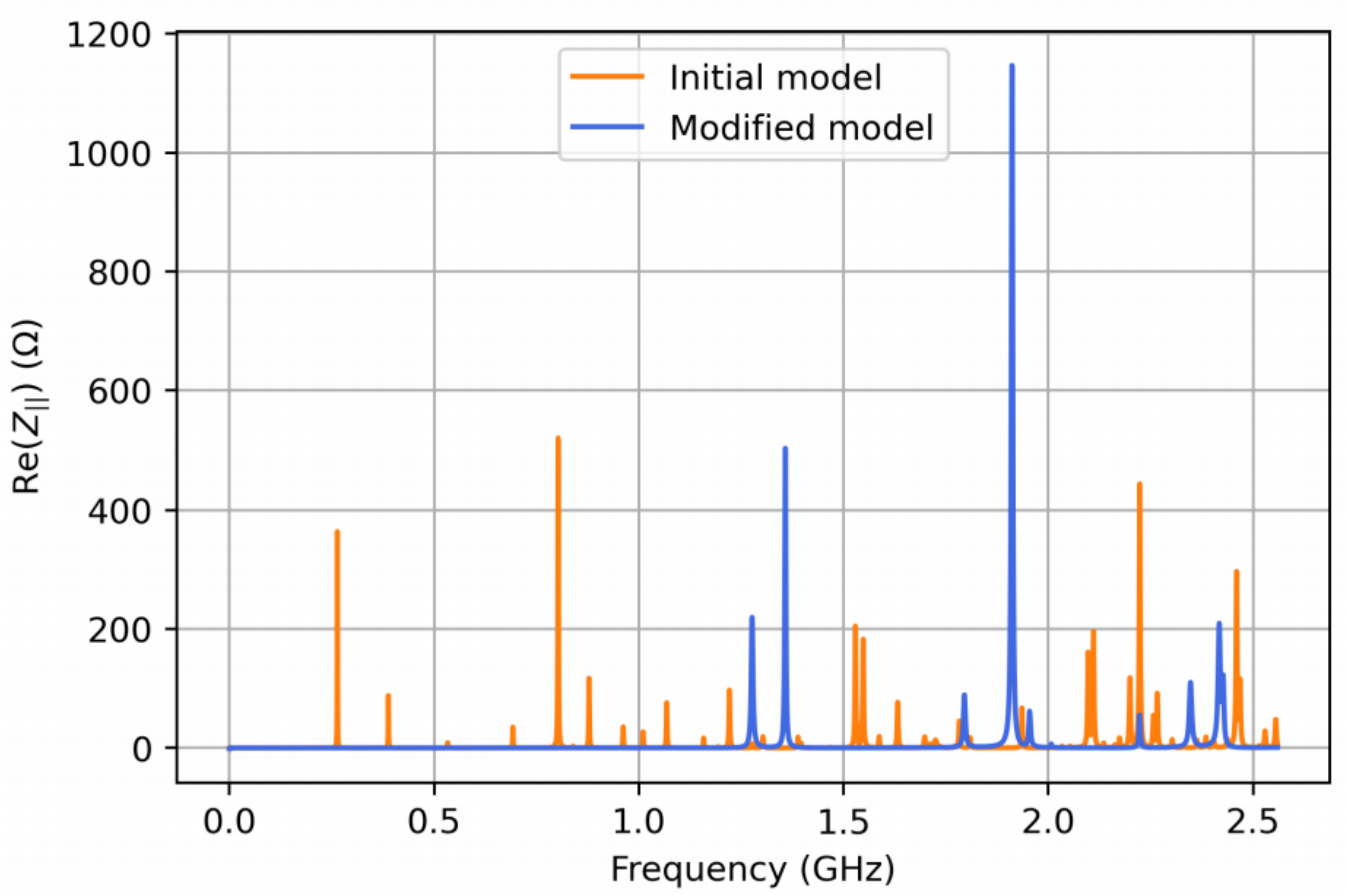
Studied Models



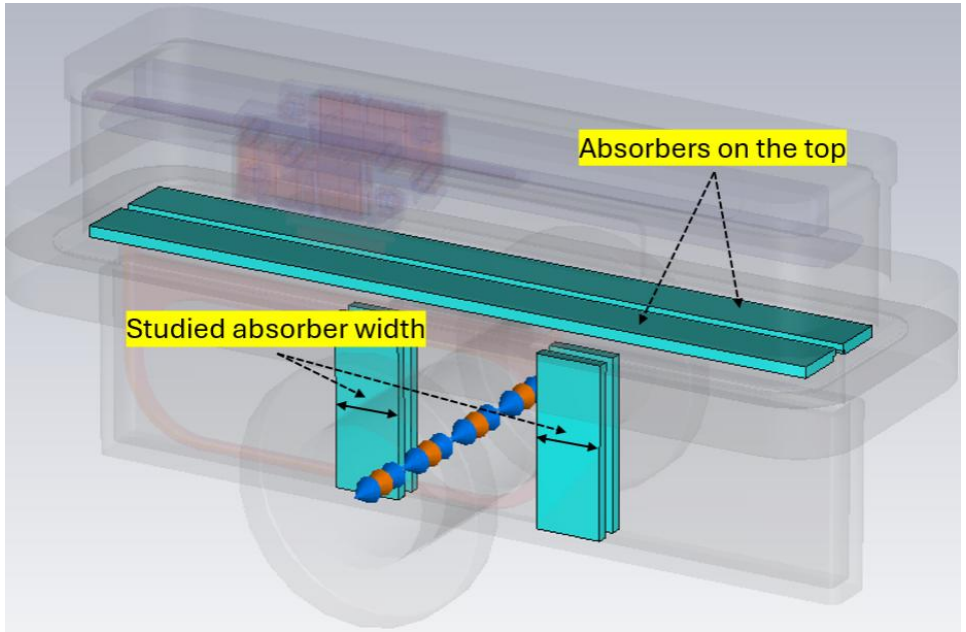
Simulation Study (1)

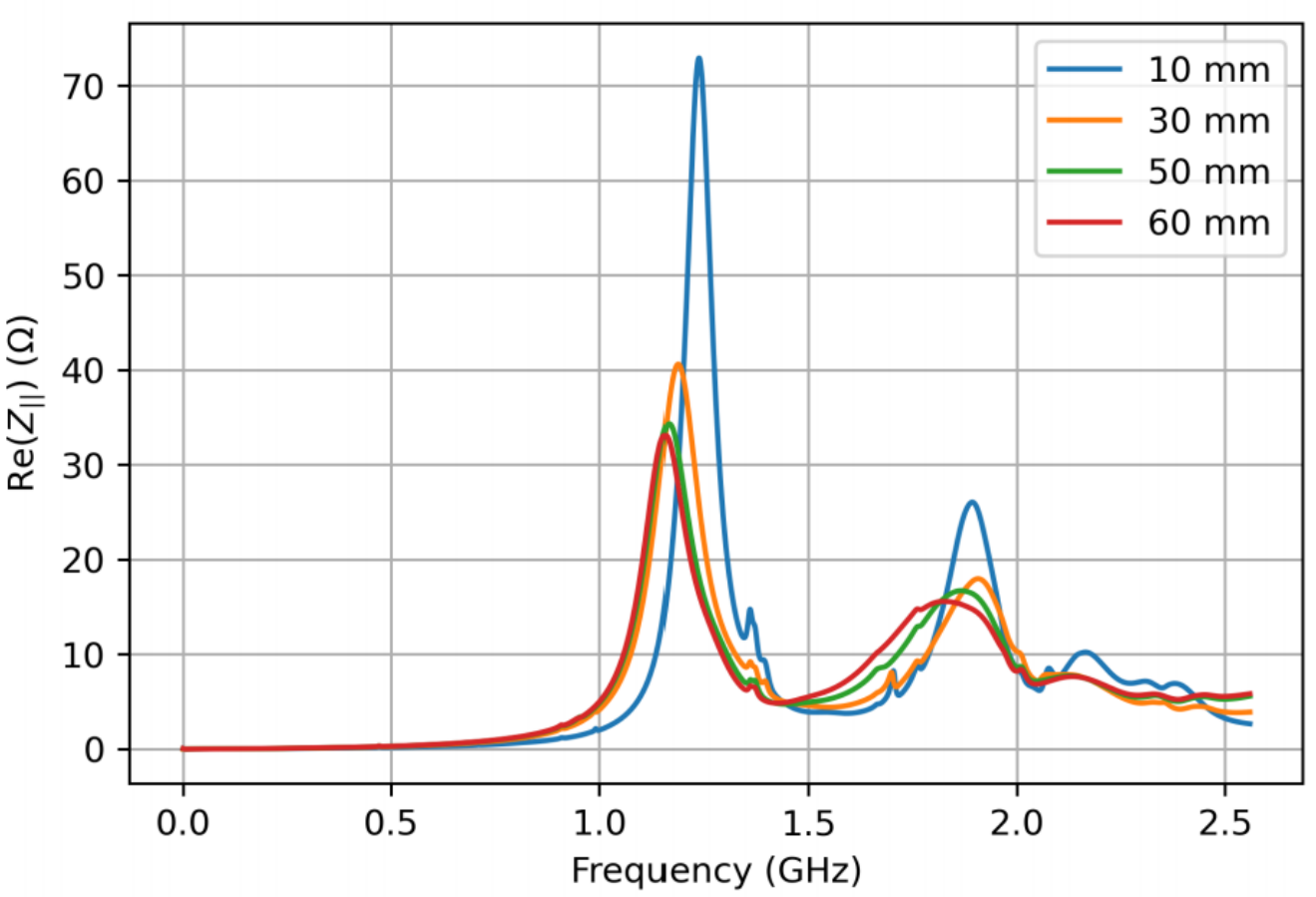




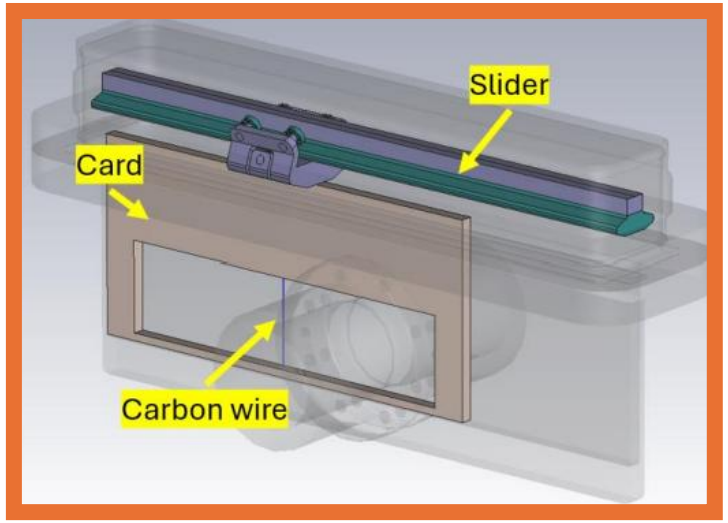


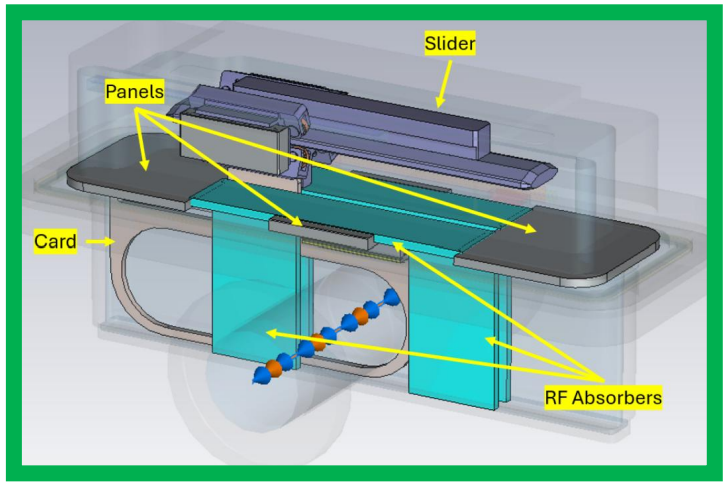
Simulation Study (2)

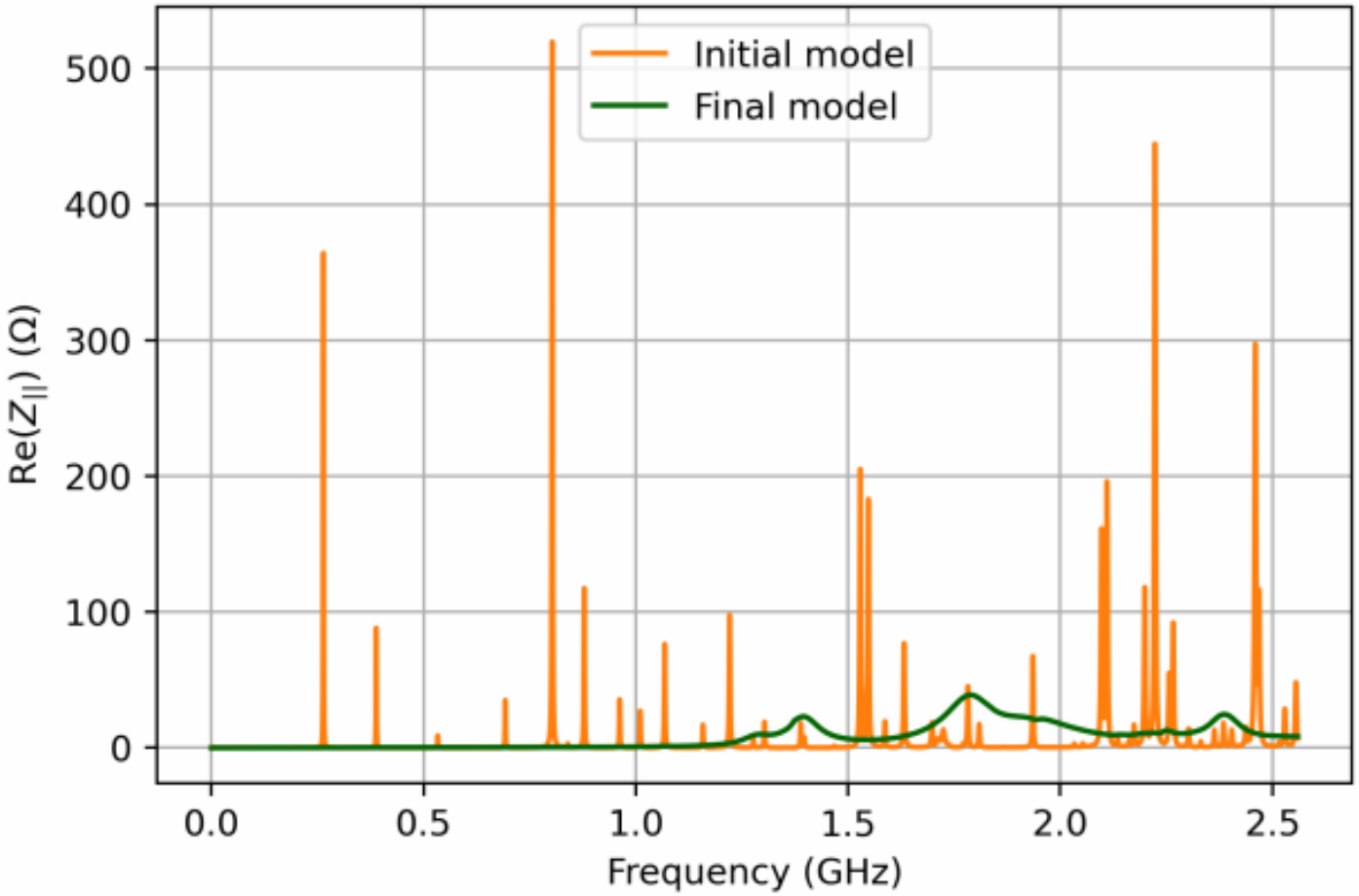




Beam Wire Scanner - Final Model

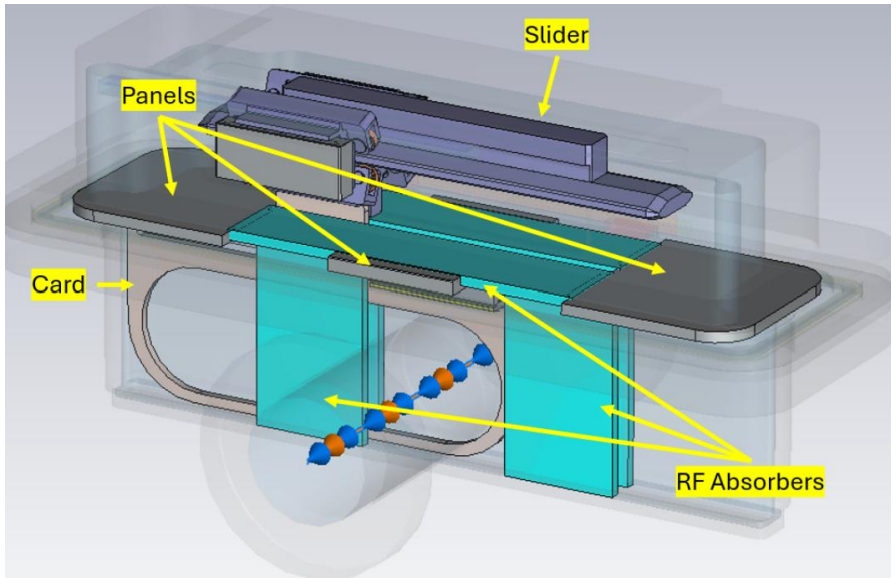


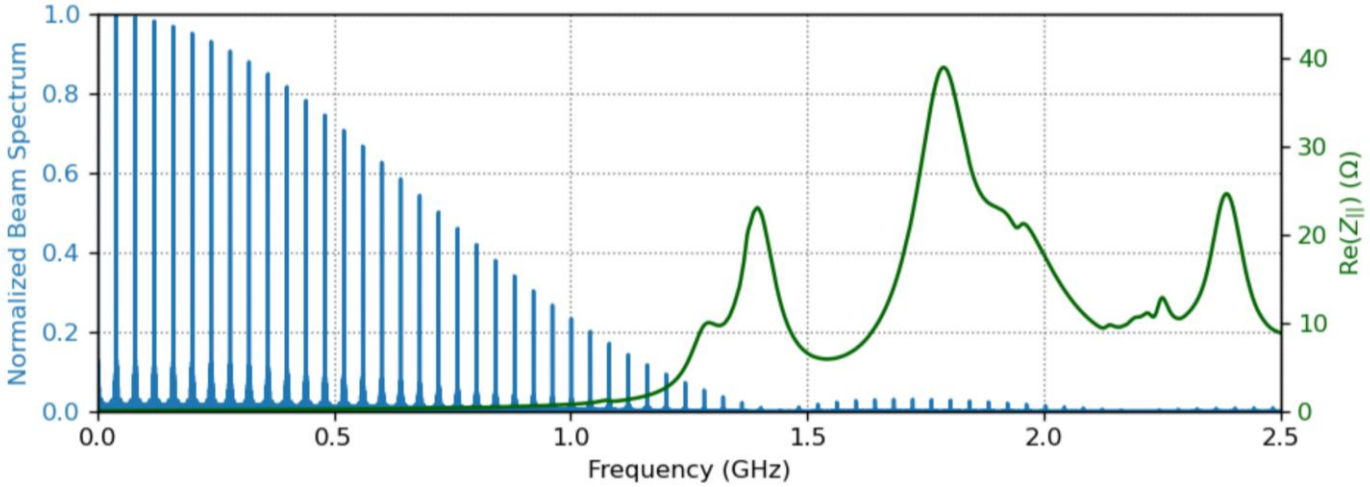




Beam Wire Scanner

Beam Induced RF Power Loss





LHC beam spectrum (q-Gaussian distribution with 25 ns spacing and bunch length 4σ = 1 ns, blue) versus BWS final model impedance (green).

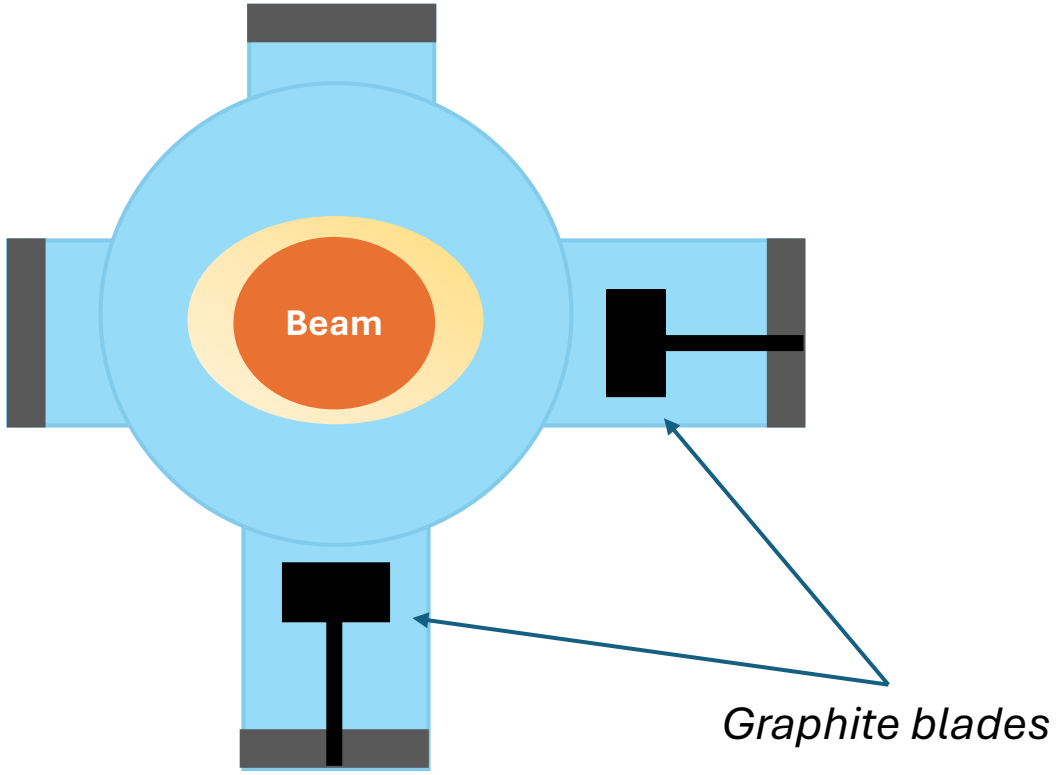
$$P_{loss} = (f_0 e N_b)^2 \sum_{p=-\infty}^{\infty} |\bar{\tilde{\Lambda}}(p\omega_o)|^2 Re[Z_{||}(p\omega_o)]$$

RF Power Loss → ~7 W

Impedance Study Examples

- Vertex Locator (LHCb)
- Beam Gas Ionization Chambers (SPS)
- Beam Wire Scanners (LHC)
- Scraper (SPS)

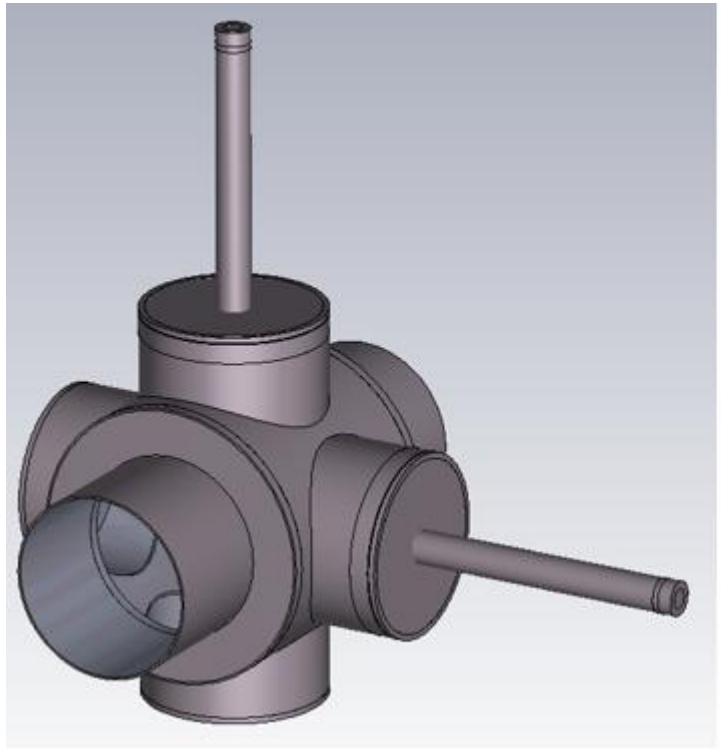
Scraper



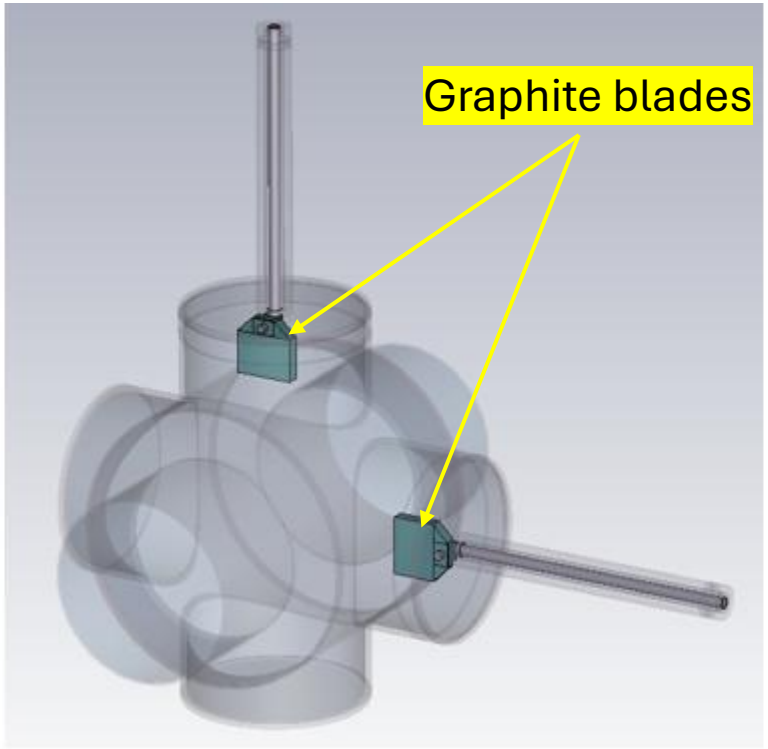
- A beam scraper cleans a particle beam by removing stray particles around its edges before the beam is sent to the next accelerator section or an experiment.
- Consisting of a chamber and movable graphite blades.

A. *Mereghetti, F. Cerutti, R. B. Appleby , "Characterization of the beam scraping system of the CERN Super Proton Synchrotron",*
B. *Phys. Rev. Accel. Beams 24, 043002 – Published 19.04.2021*

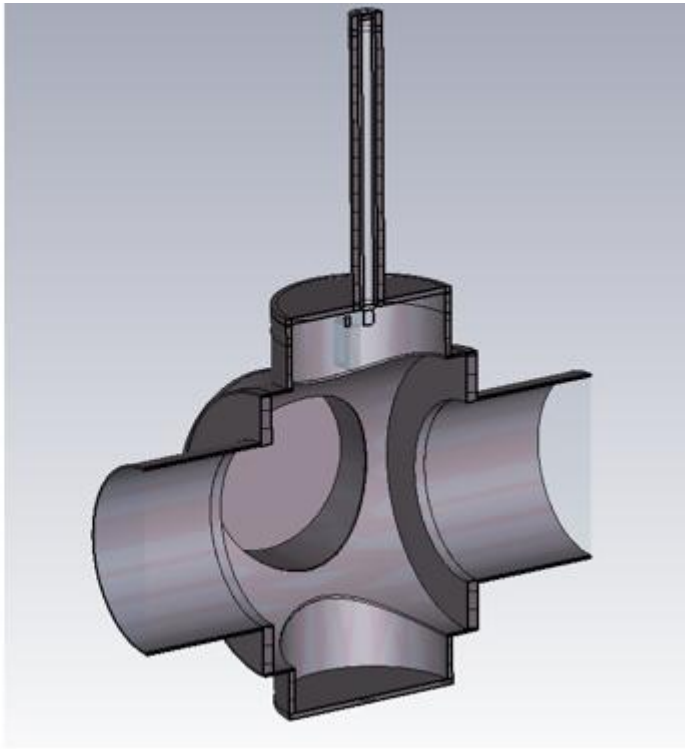
Scraper - Initial Model



Stainless Steel Tank

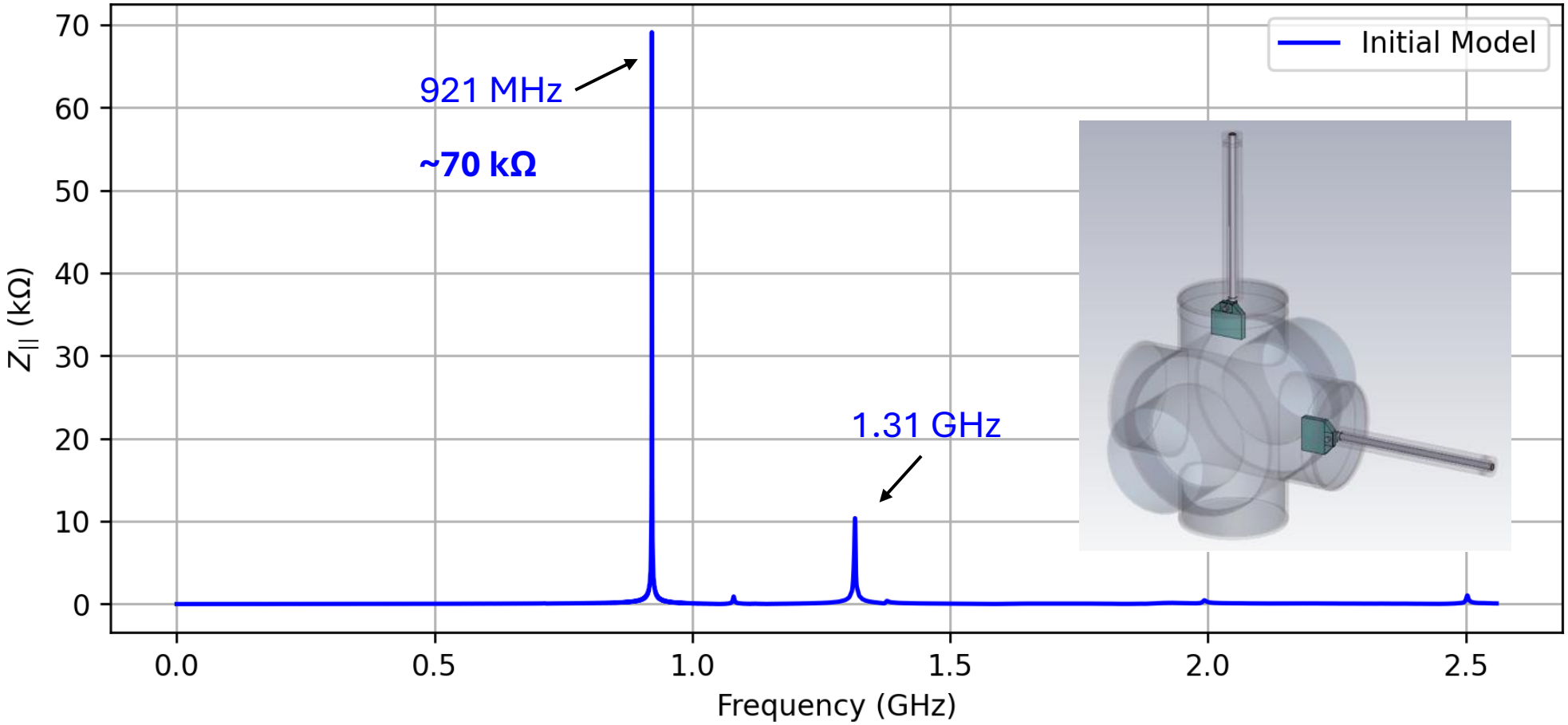


Internal View

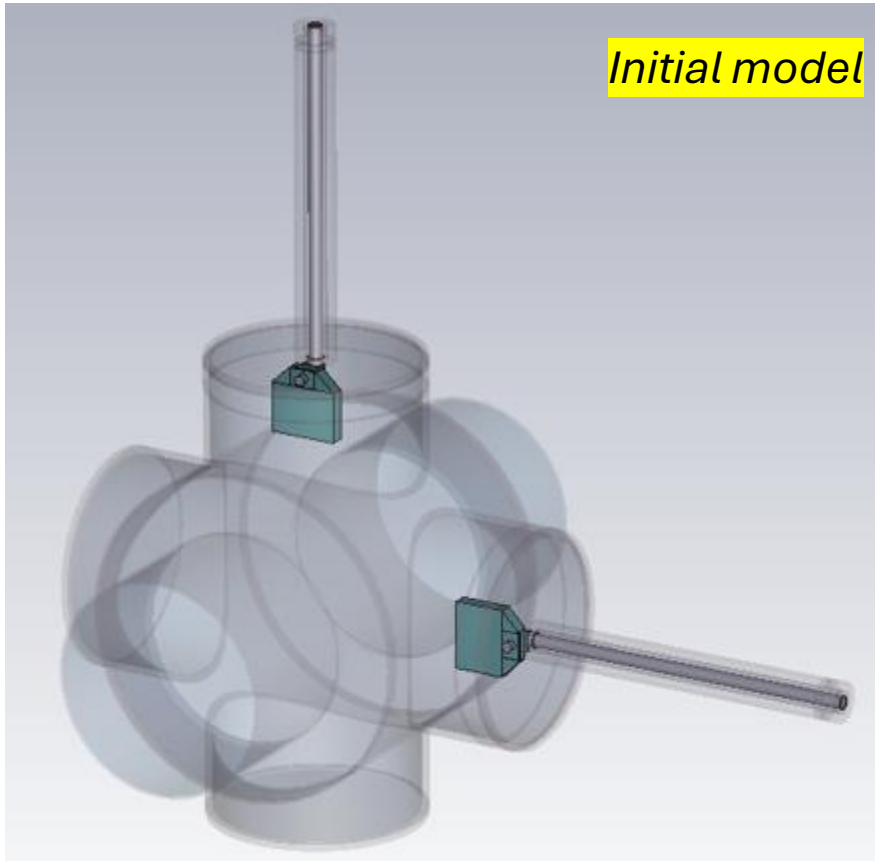


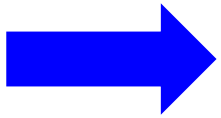
Cross-sectional View

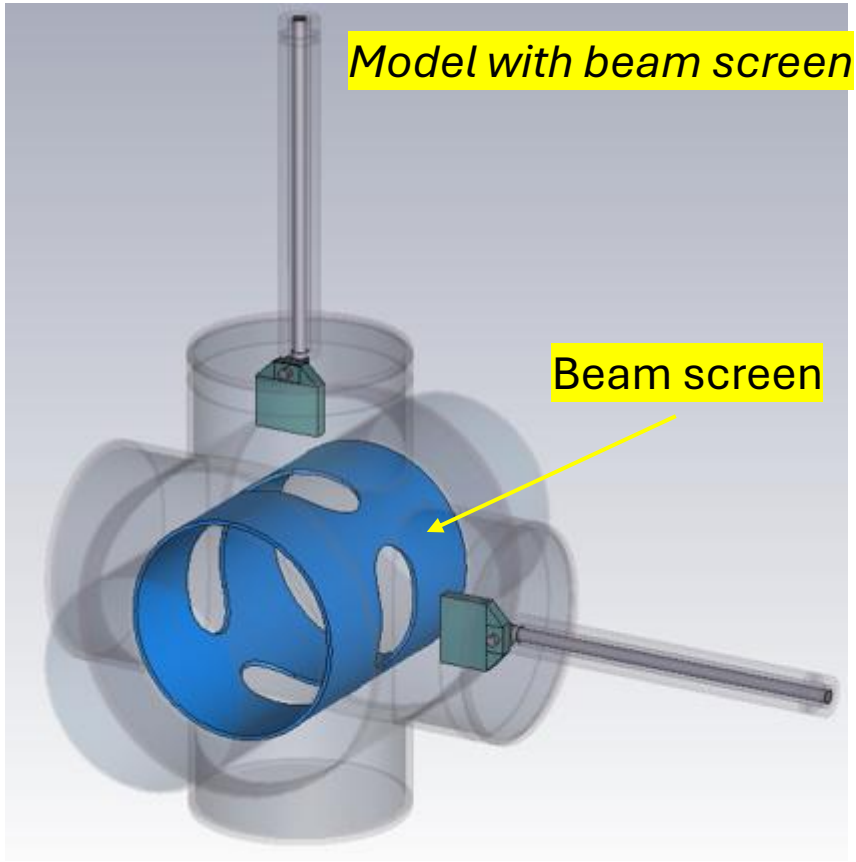
Initial model – Longitudinal impedance response



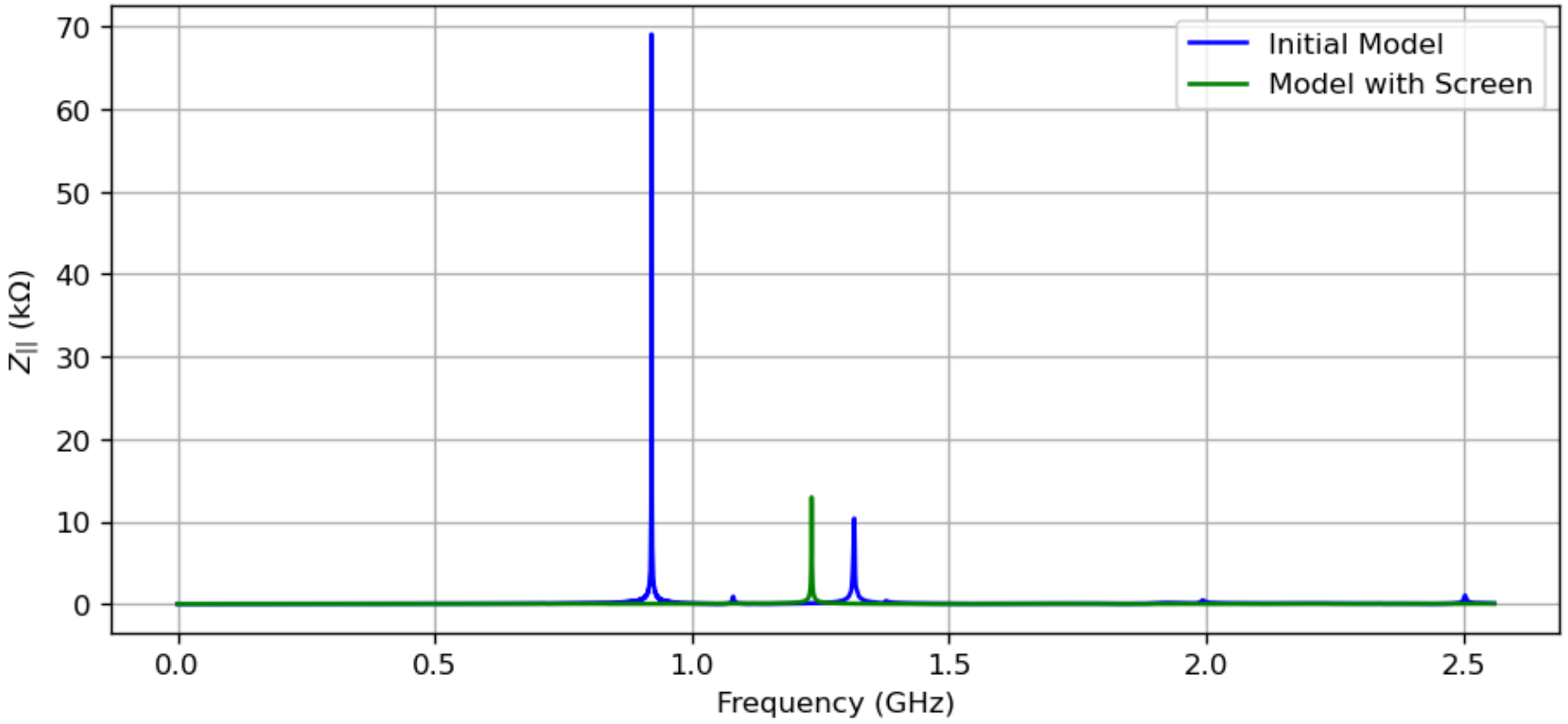
Model with beam screen

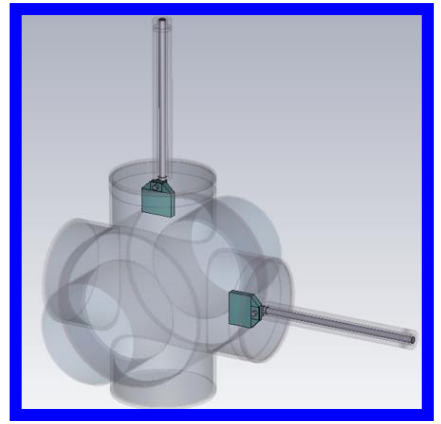


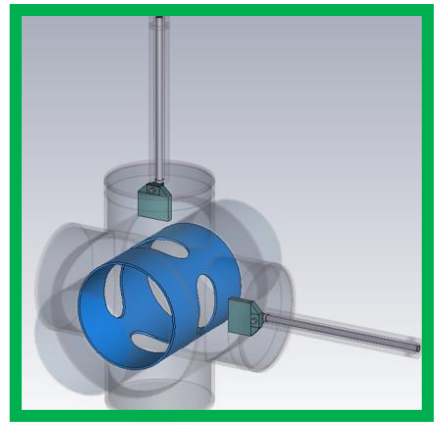




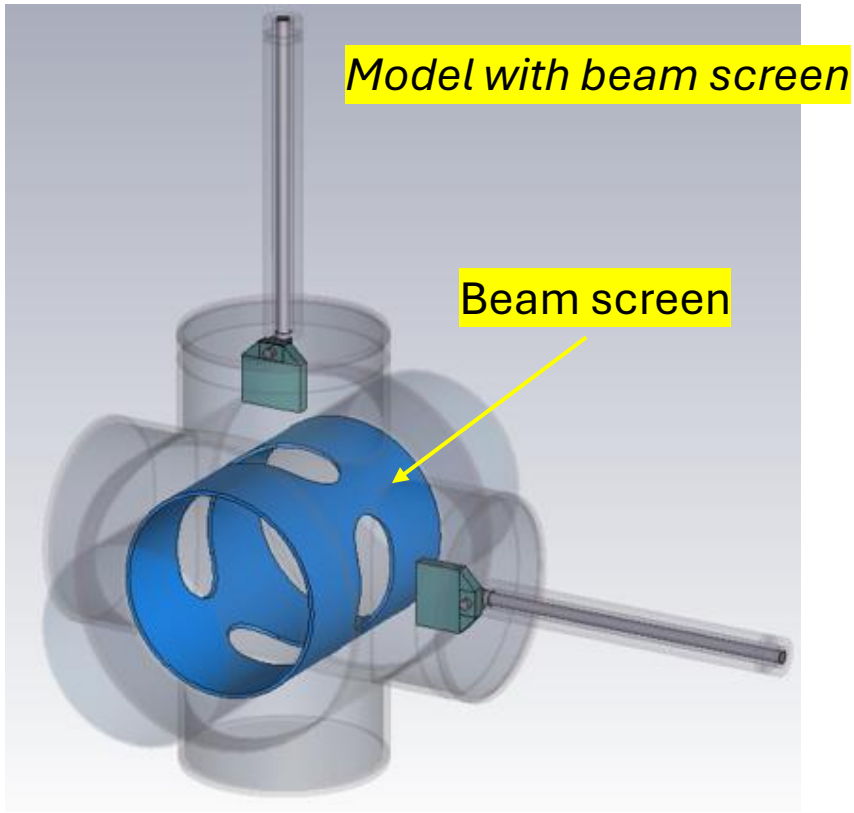
Model with beam screen

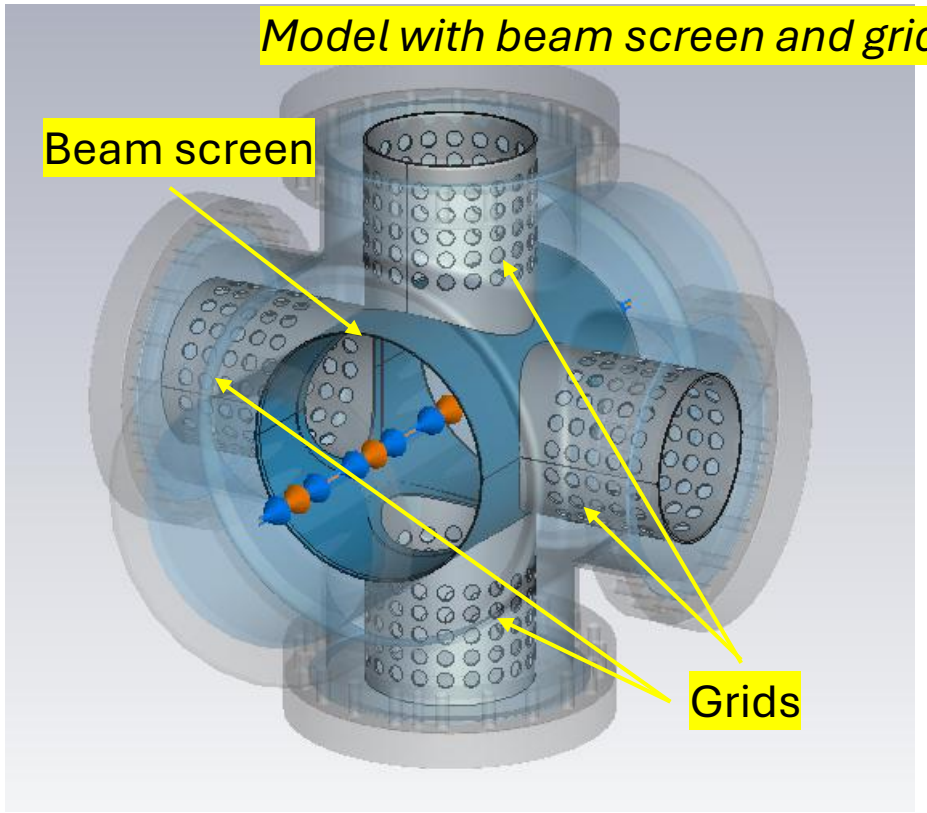




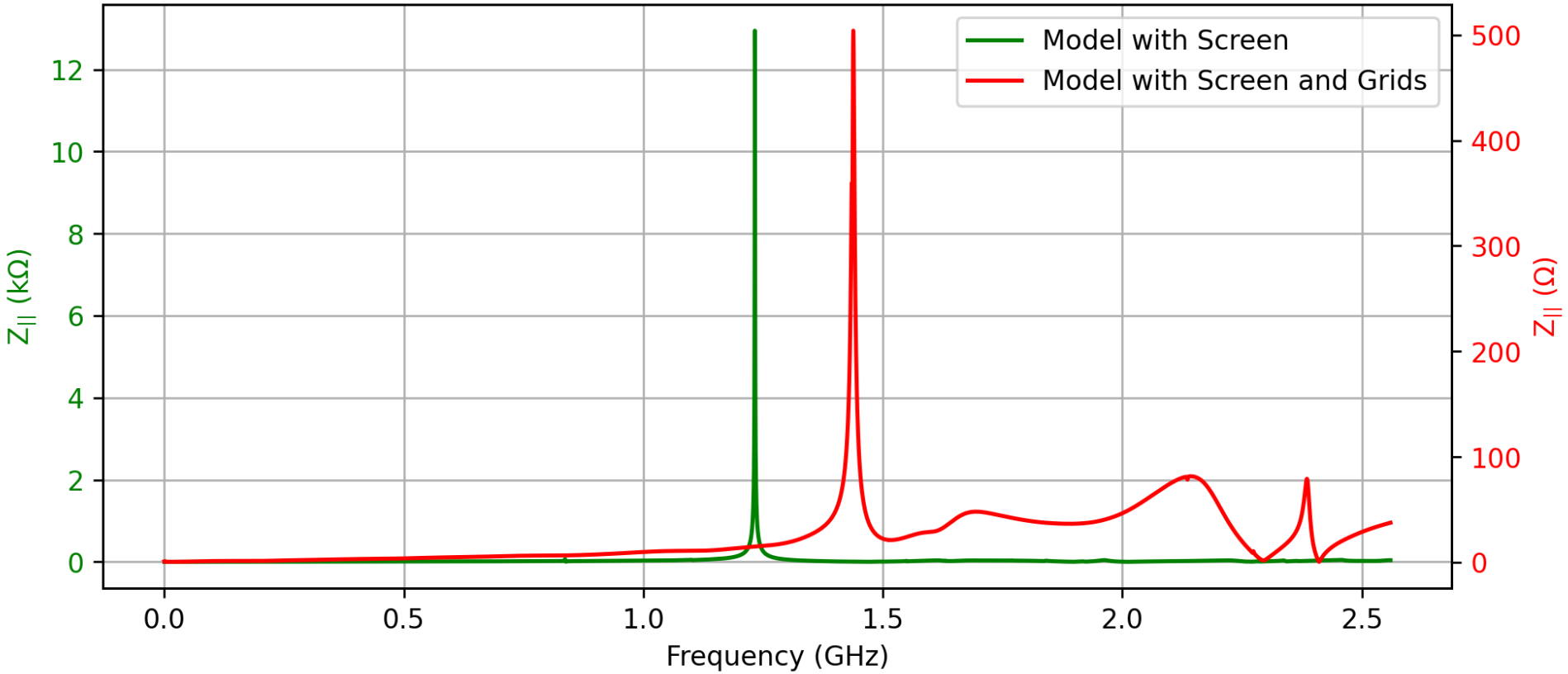


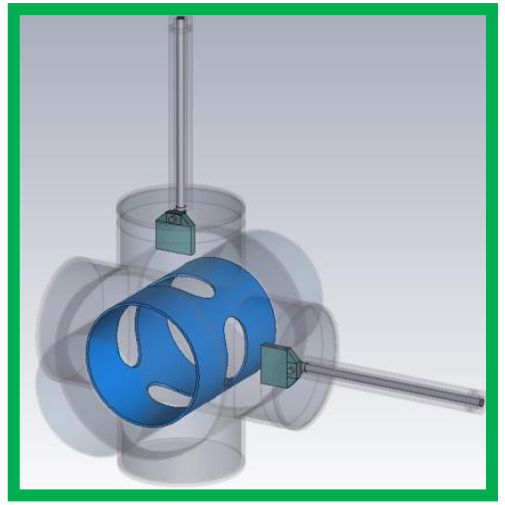
Model with beam screen and grids

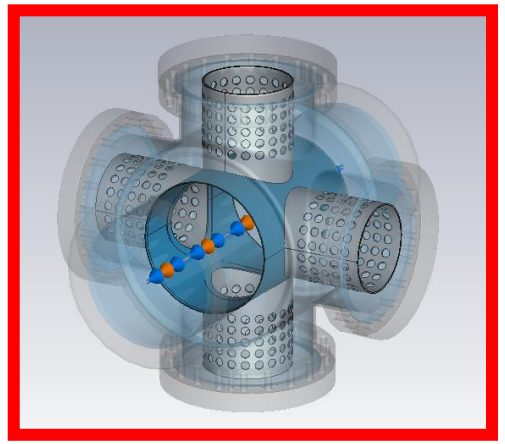




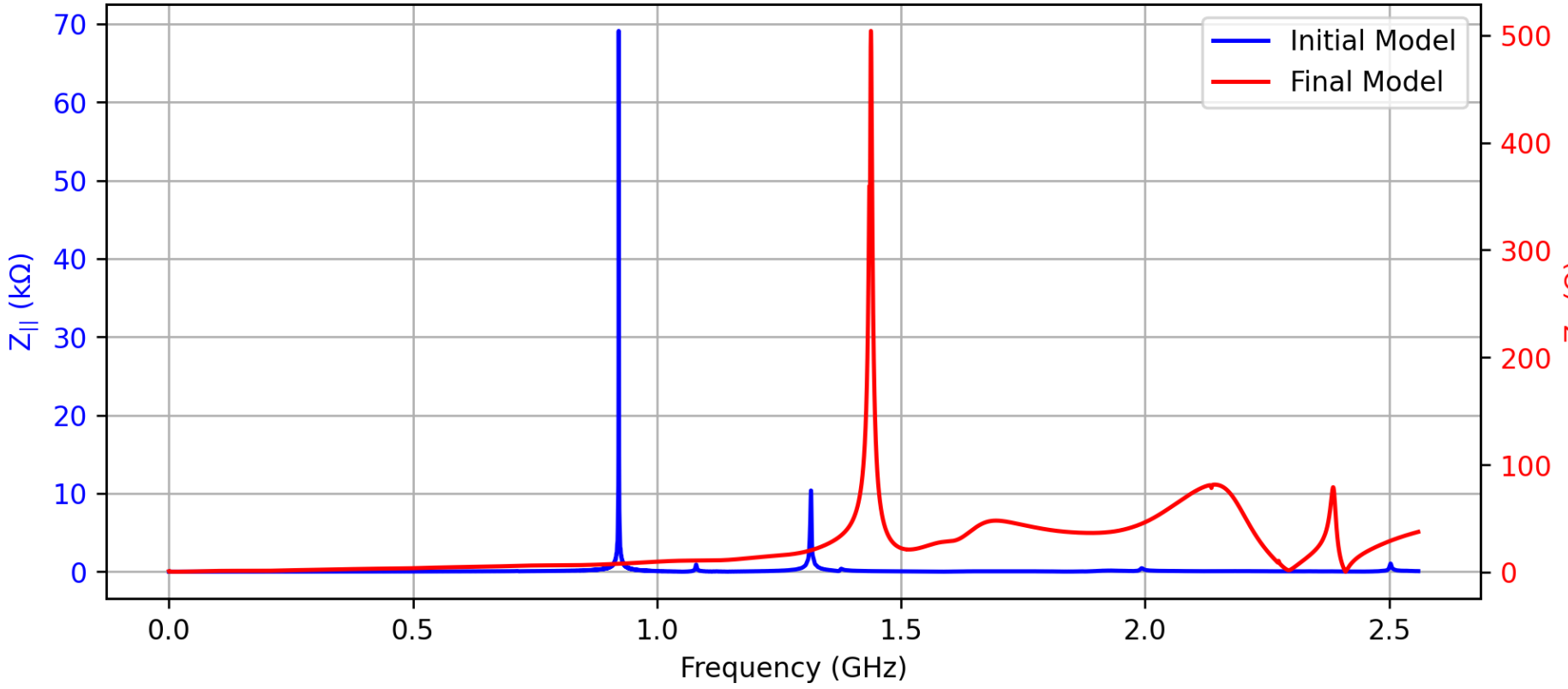
Model with beam screen and grids

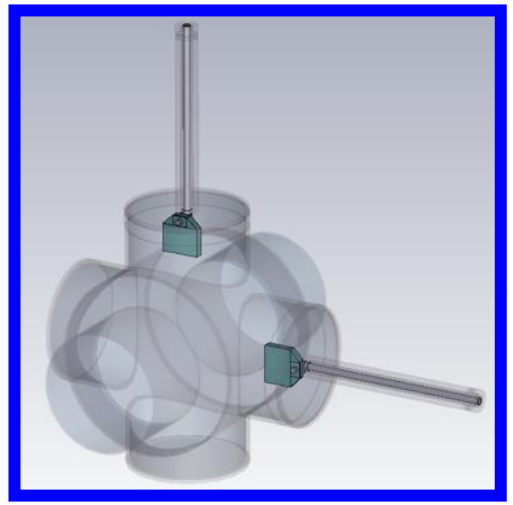


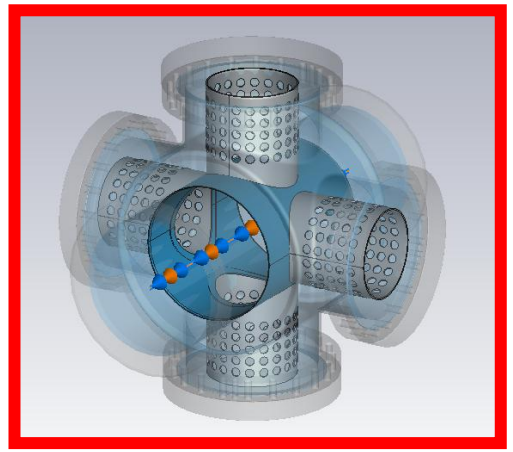




Initial vs Final Model – Longitudinal impedance Response

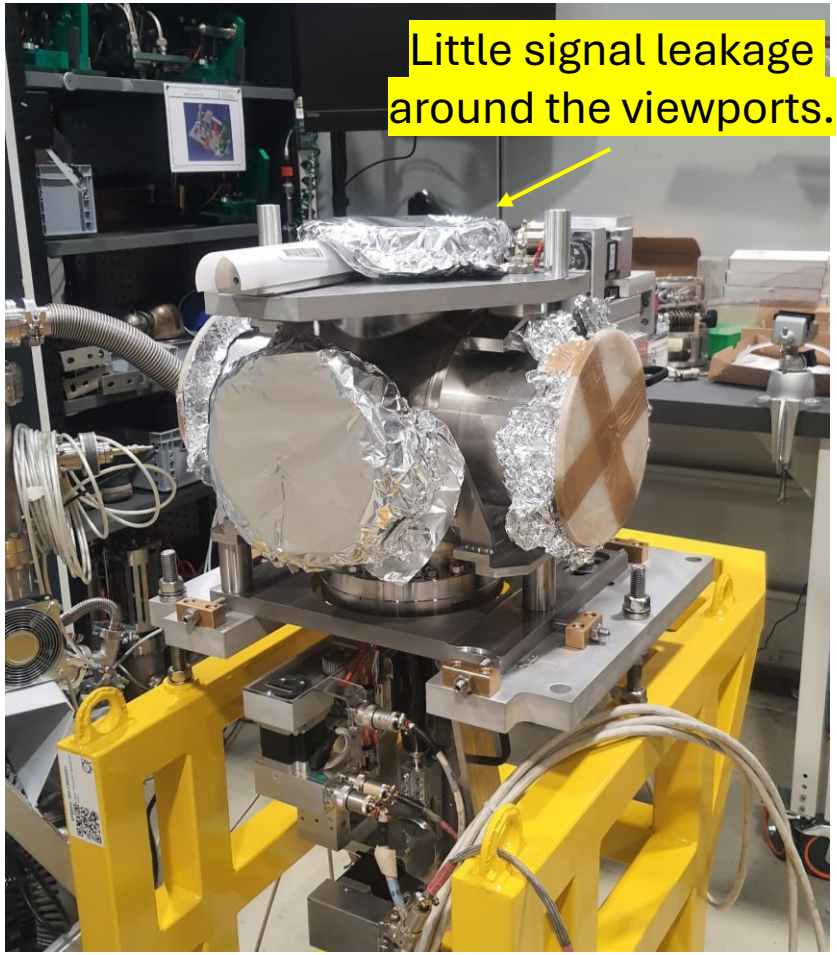


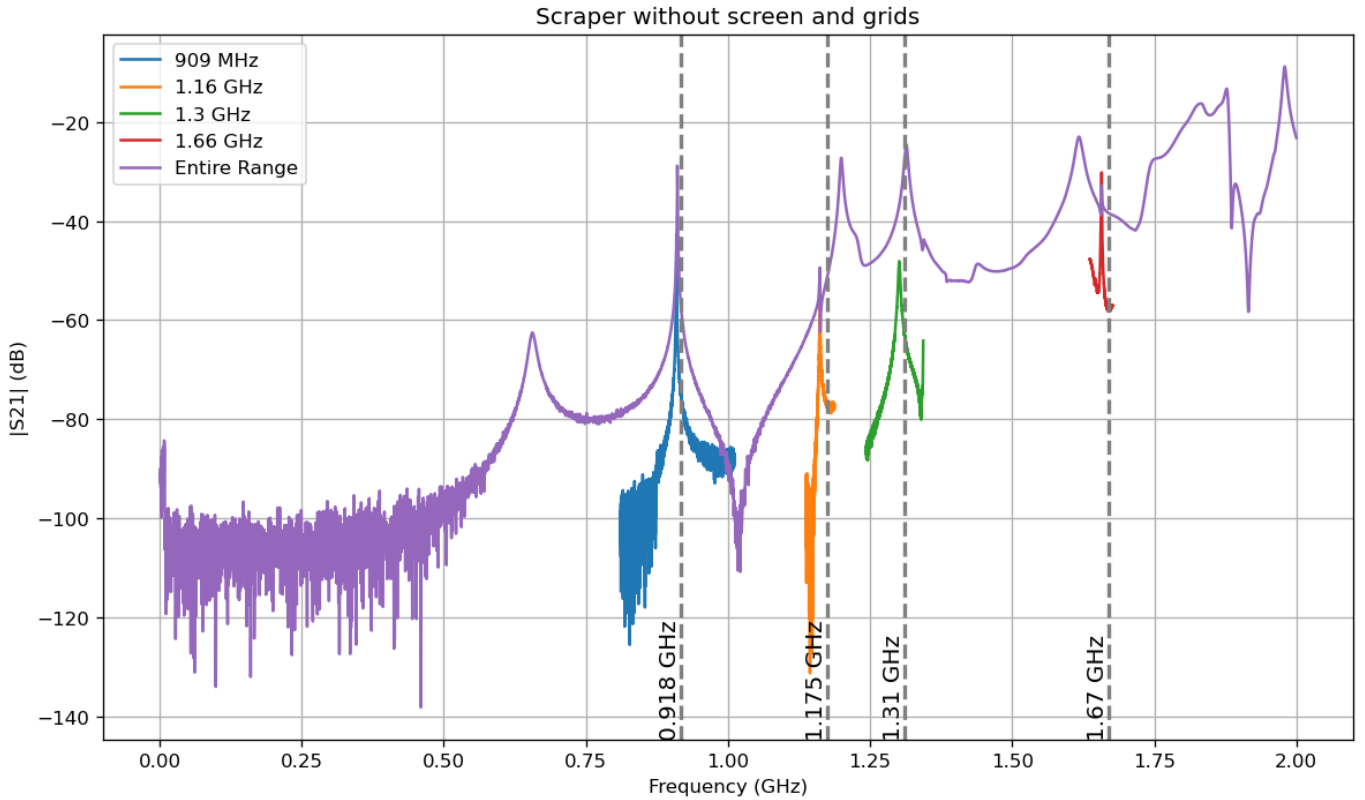




RF Measurements

Scraper without screen





✓ The detected modes (dashed grey lines) showed small deviations on the resonant frequencies compared to simulation results due to the simplified simulation geometry and little signal leakage around the viewports.

Summary

- We described the mission and responsibilities of the CERN Impedance Working Group.

- We discussed the example impedance studies of Vertex Locator, Scraper and new generation diagnostic elements; beam gas ionization chambers, wire scanners.

- Some documents for more information:

  - Impedance reduction of the beam gas ionization monitors for the CERN SPS

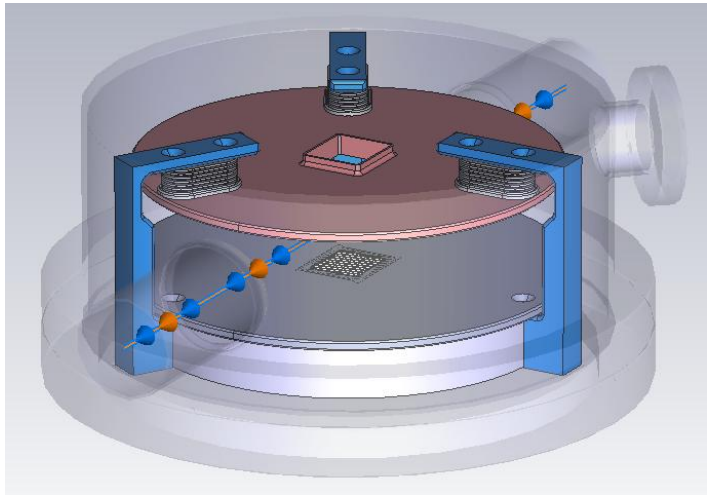
  - Impedance Reduction of the Beam Wire Scanners for the CERN LHC

Thanks for your attention!

Backup Slides

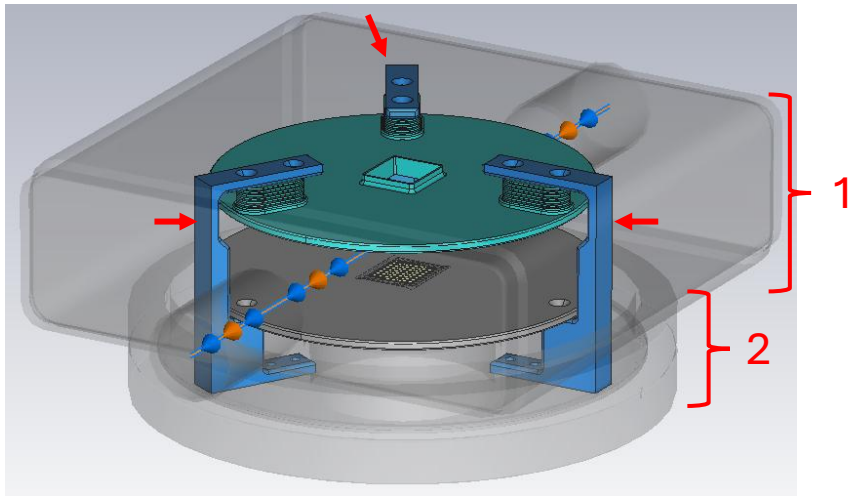
LHC-BGI CST Models

1 Circular Design



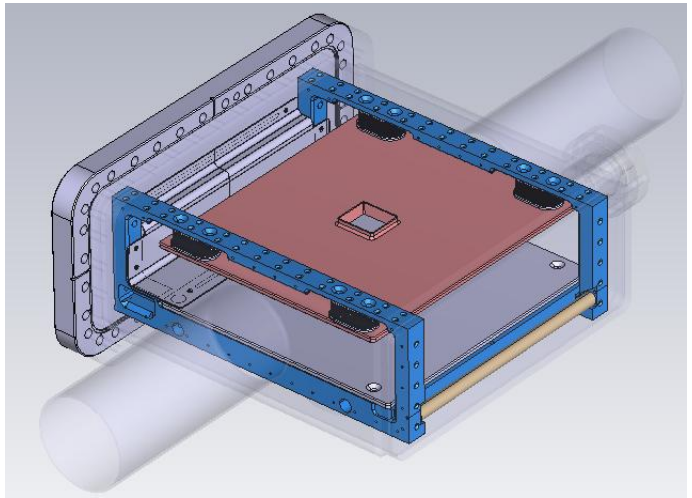
- Circular tank will cause a strong resonance.
- RF fingers can be added to contact the chamber.
- Smaller tank?

2 Rectangular Design



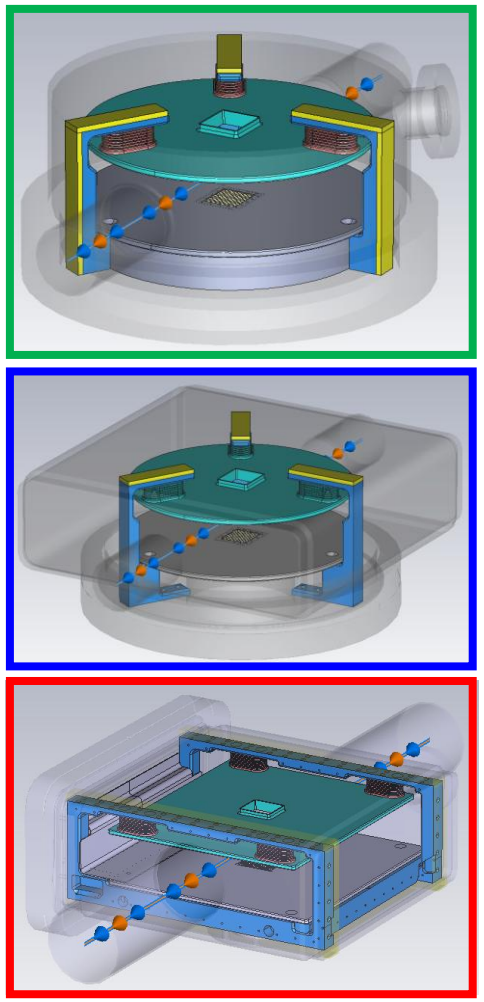
- Two resonators (~coupling and cause resonances) -> (top part (1), bottom part (2))
- RF fingers? (fully?)
- Adding an RF contact between the tanks?

3 SPS-like BGI Design

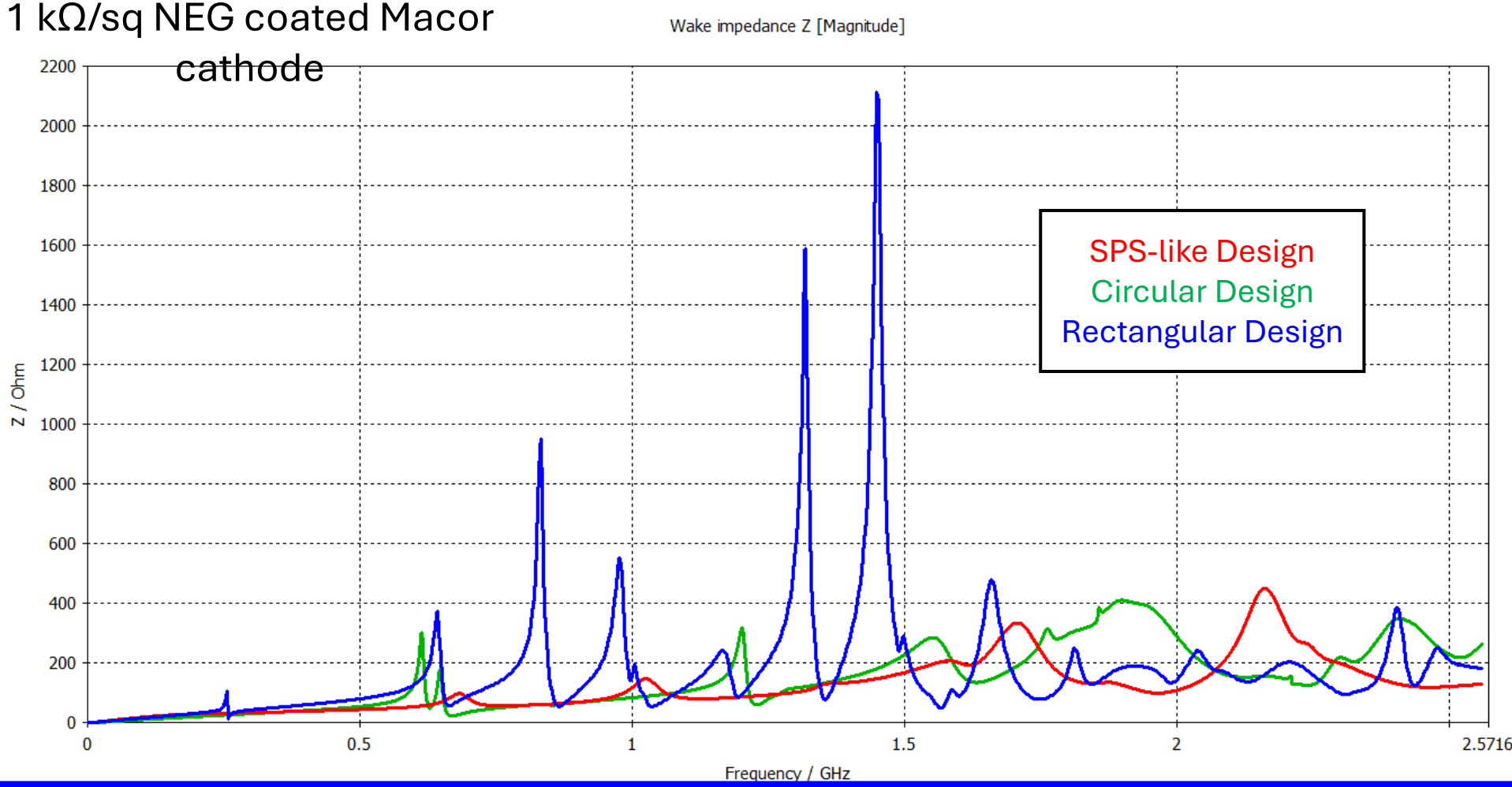


- RF fingers can be added.
- Impedance response like SPS-BGI.
- Rod is not necessary if the cathode is coated.

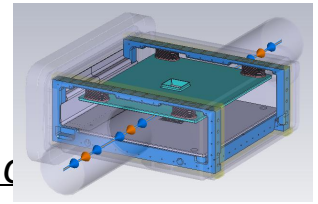
LHC-BGI Comparison of The Models



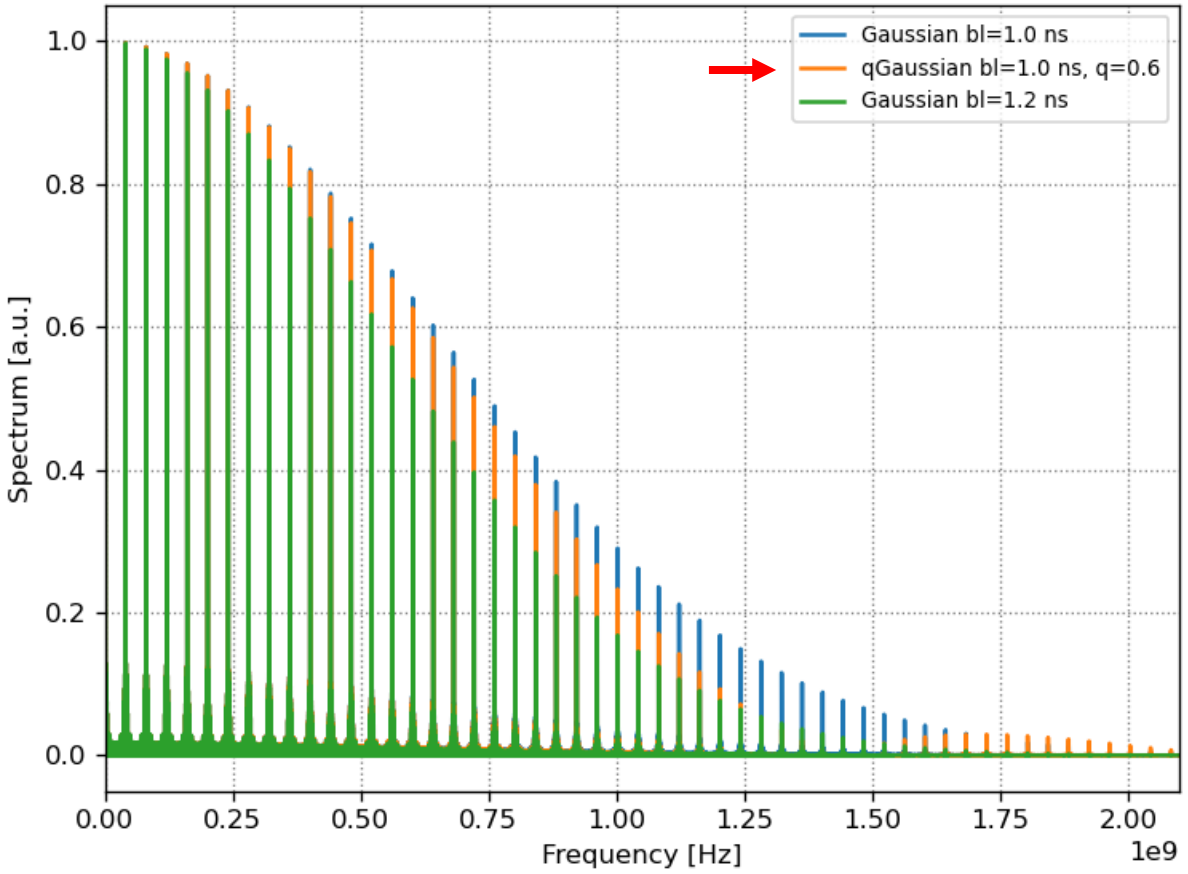
1 kΩ/sq NEG coated Macor cathode



Remark on HL-LHC Beam Spectrum

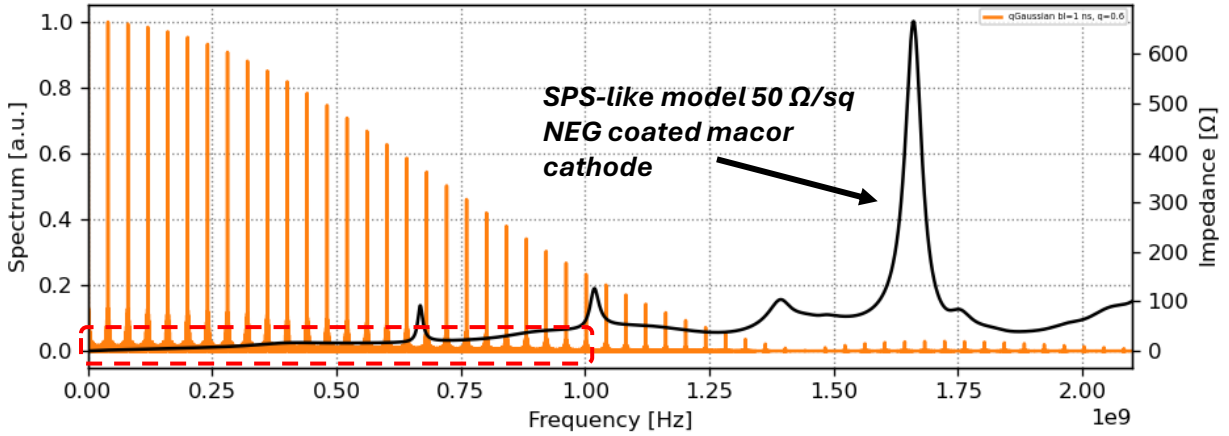


Beam Spectrum for Different Bunch Shapes

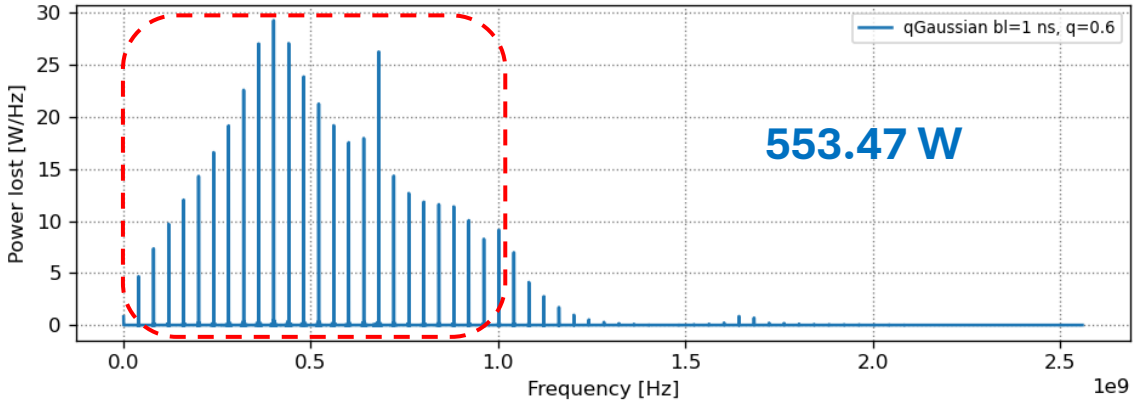


Beam Induced Heating Computation code - BIHC

Beam Spectrum vs BGI Impedanc

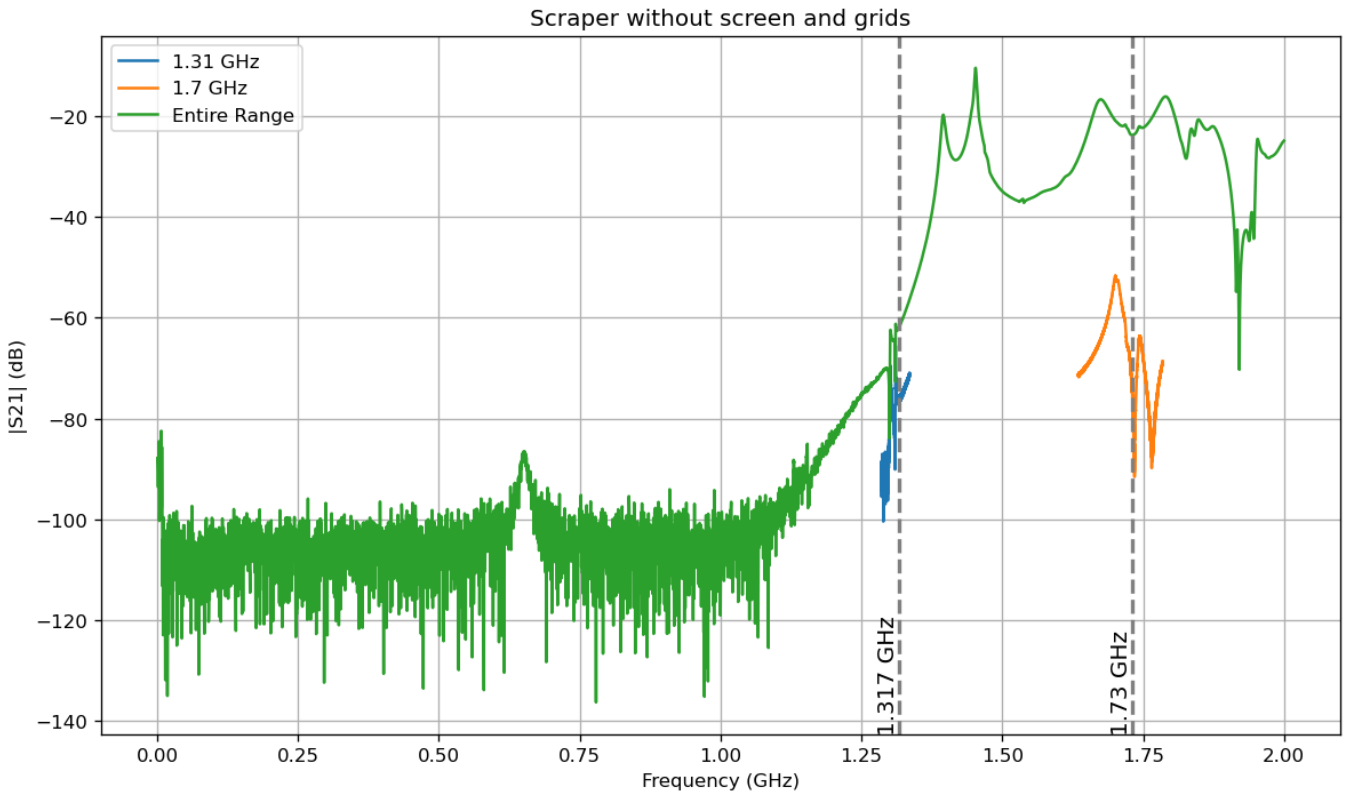


Power Loss Contribution



RF Measurements - Scraper

Scraper with screen and grids



✓ Many of the modes disappeared after installing the screen and grids. Two of the modes (dashed grey lines) were detected with a little signal magnitude.

Beam Parameters

	Flat-bottom	*Flat-top*
Bunch parameters		
Binomial exponent	1.5	
Bunch length (ns)	3.4	1.65
Intensity per bunch (10^{10} ppb)	26	23
Line density	binomial	
Filling scheme		
Buckets between batches	40	
Buckets between bunches	5	
Buckets between fills	1	
Number of batches	4	
Number of bunches	72	
Number of fills	1	
General parameters		
Circumference (m)	6911.5	
Momentum (10^9 eV/c)	26	450
Particle type	proton	
Transition gamma	17.95	
RF Parameters		
Harmonic number	4620	
RF voltage (10^6 V)	10	
RF phase	0	

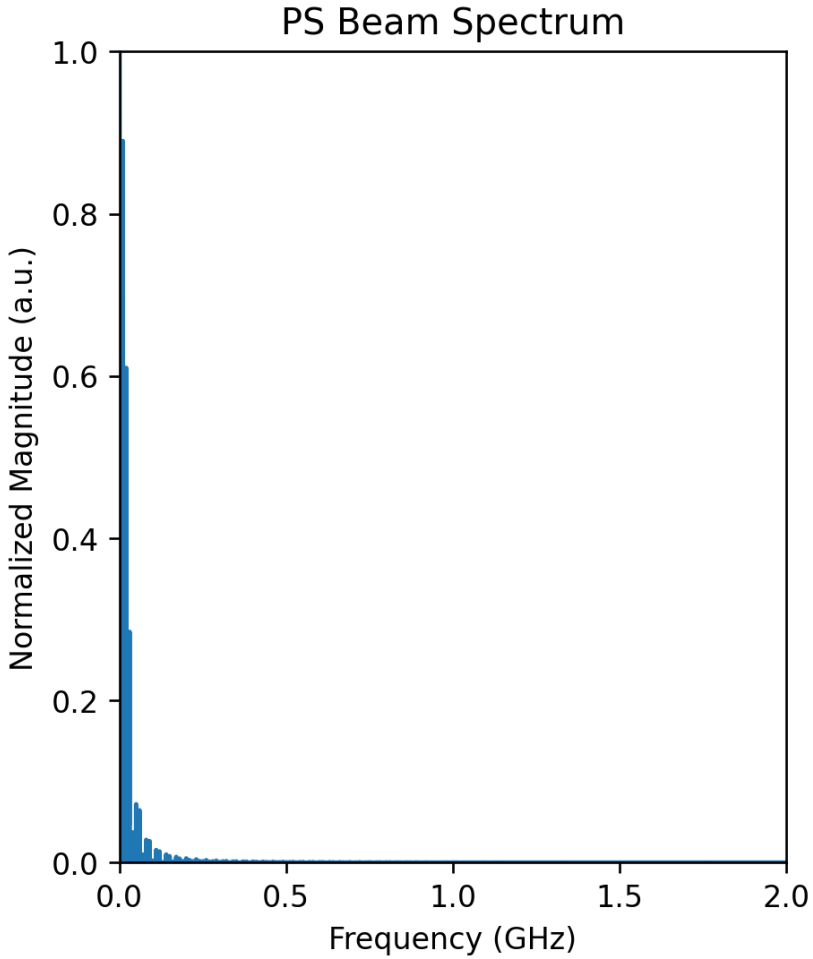
References

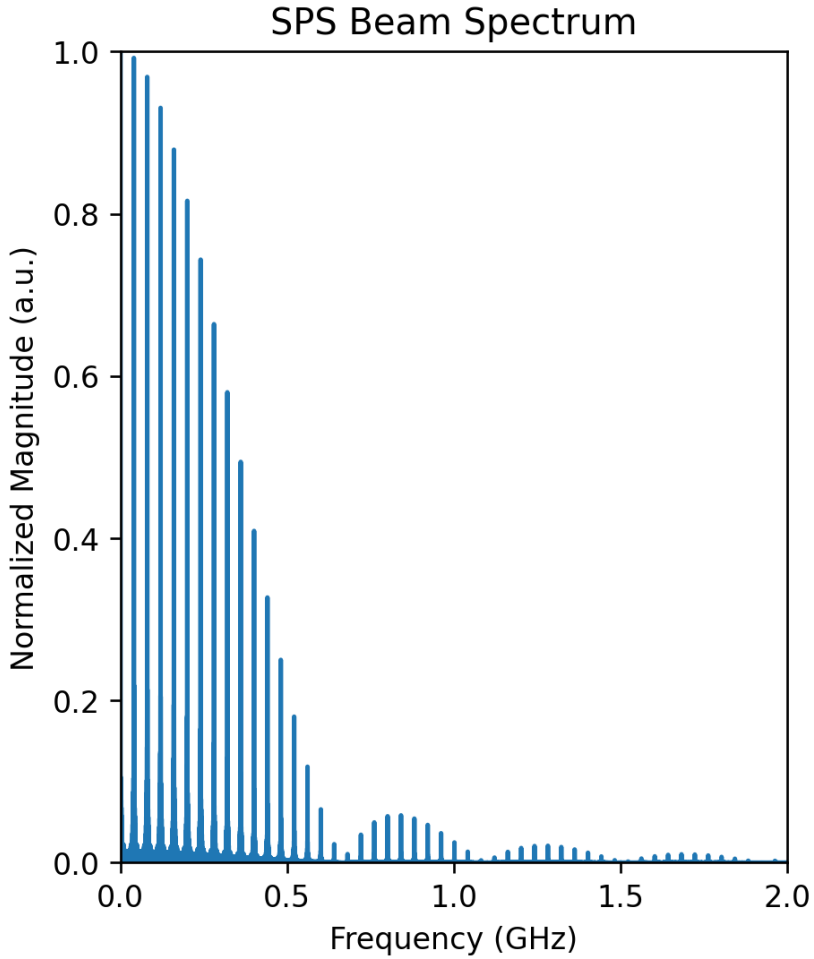
G. Papotti, private talk.

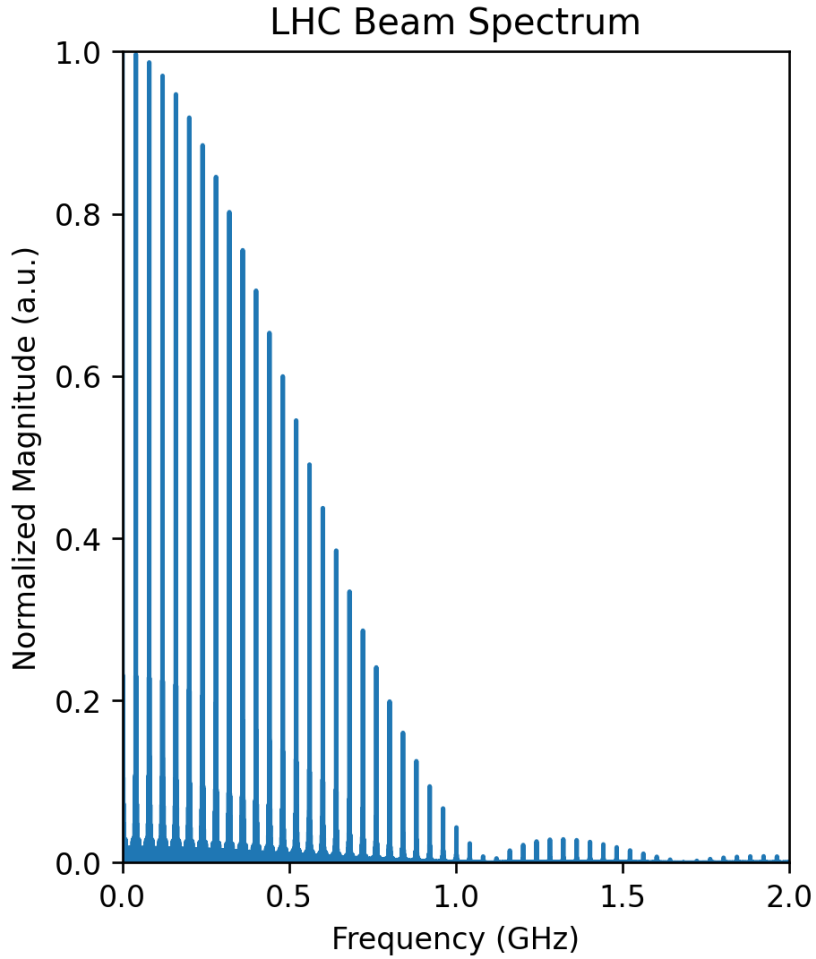
H. Damerau, private talk.

G. Rumolo, CERN Engineering; Equipment Data Management Service, LIU Proton Beam Parameters, 2017

Remark on Beam Spectrums (1)

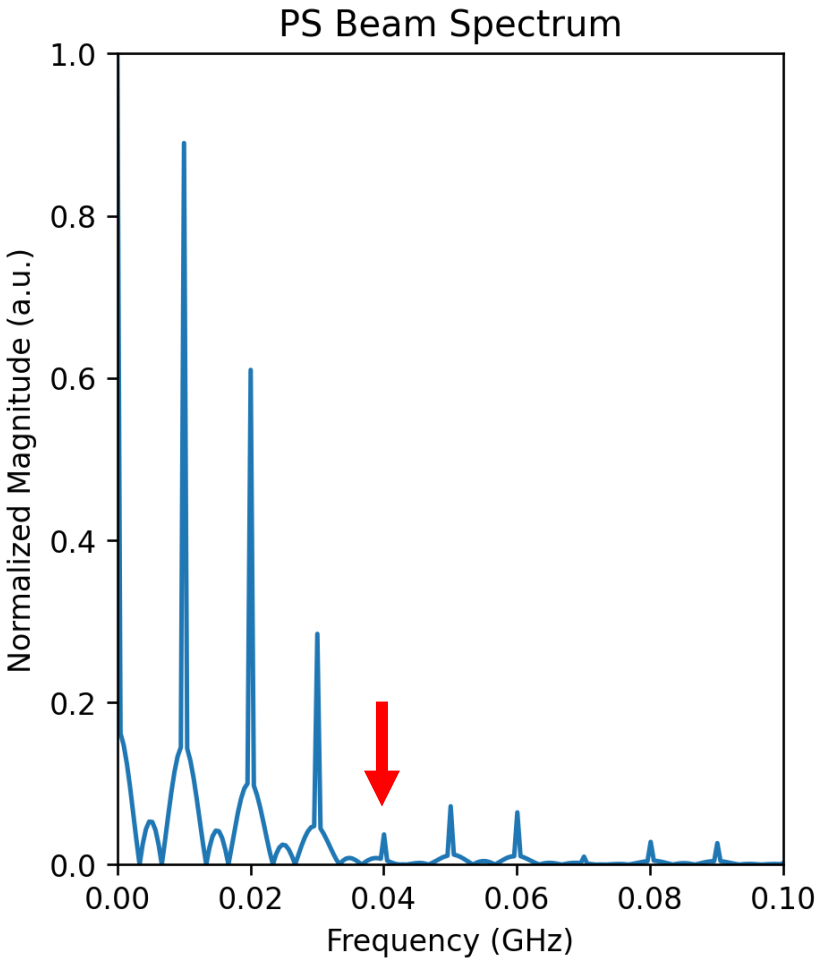


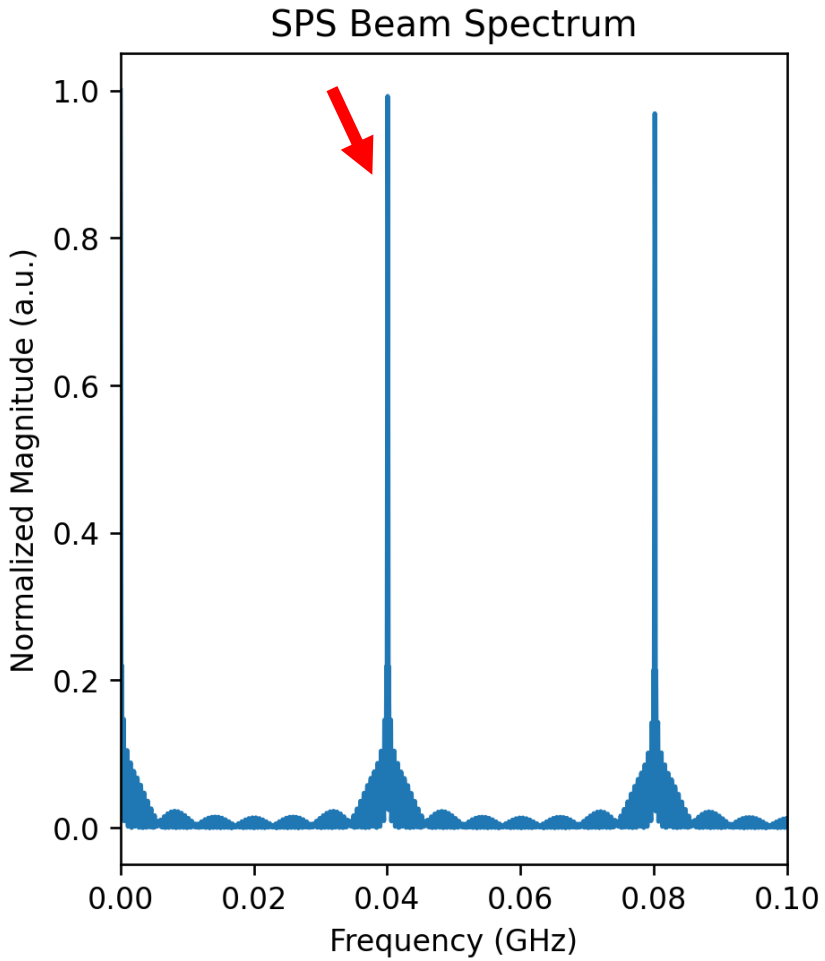


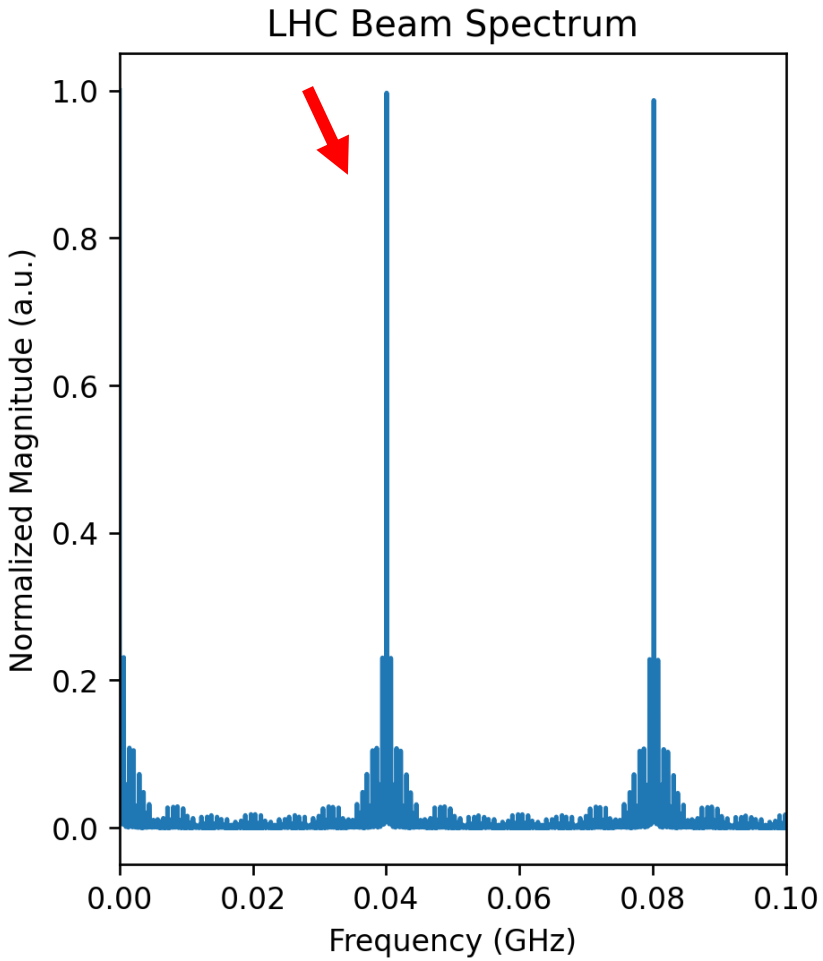


Beam spectrums were plotted by BLonD.

Remark on Beam Spectrums (2)



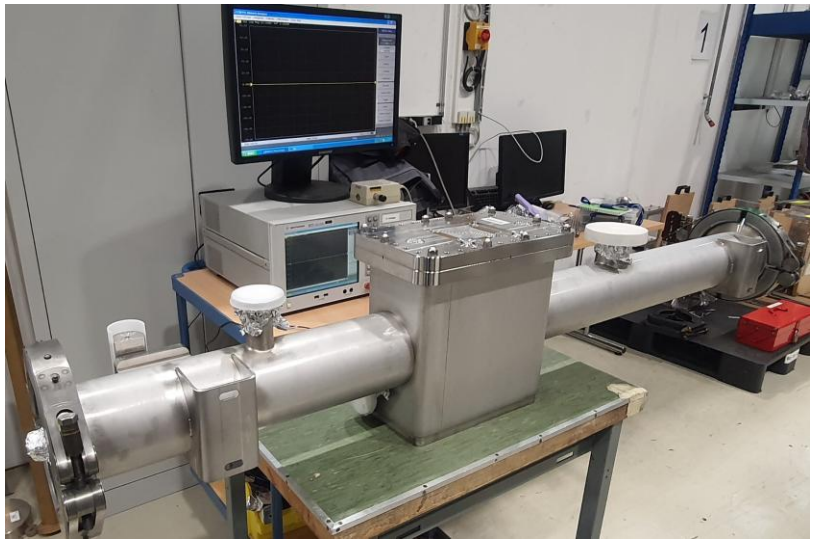




Beam spectrums were plotted by BLonD.

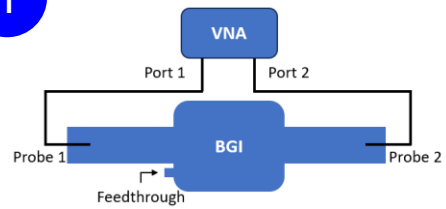
RF Measurements of BGI

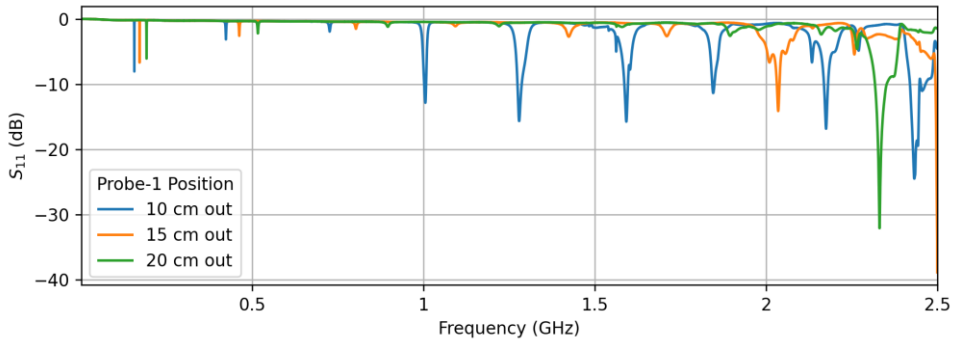
Manufactured BGI



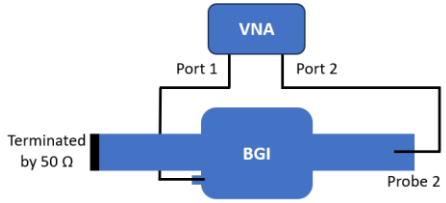
- Non-uniform resistivity on the NEG coated cathode (600 Ω/sq on bottom, 1.8 kΩ/sq on top).
- Restrictions on the probe connections.
- 3 different configurations.
- Only probe modes appeared.
- No cavity resonances were detected.

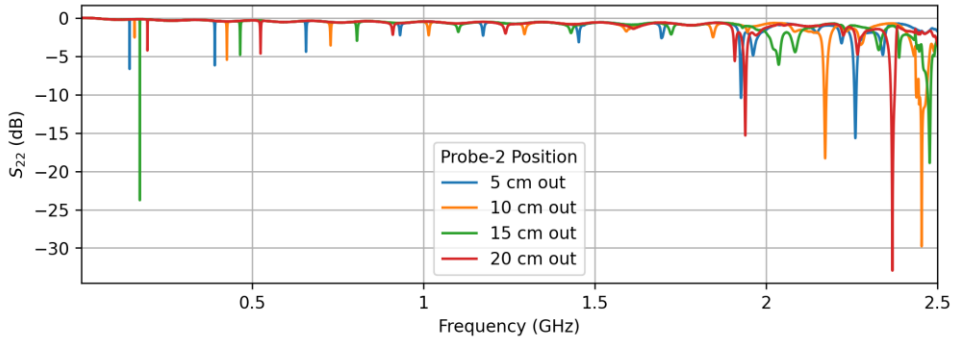
1



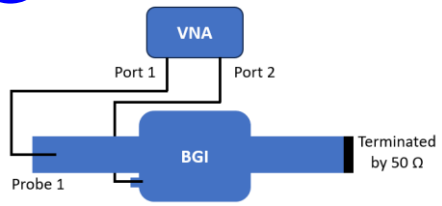


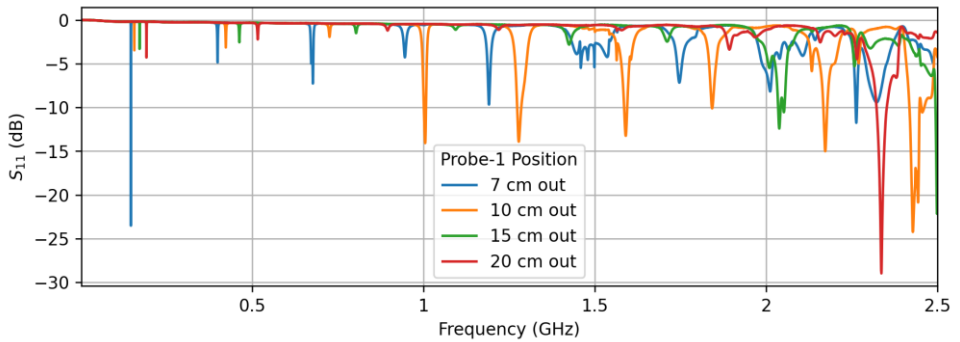
2





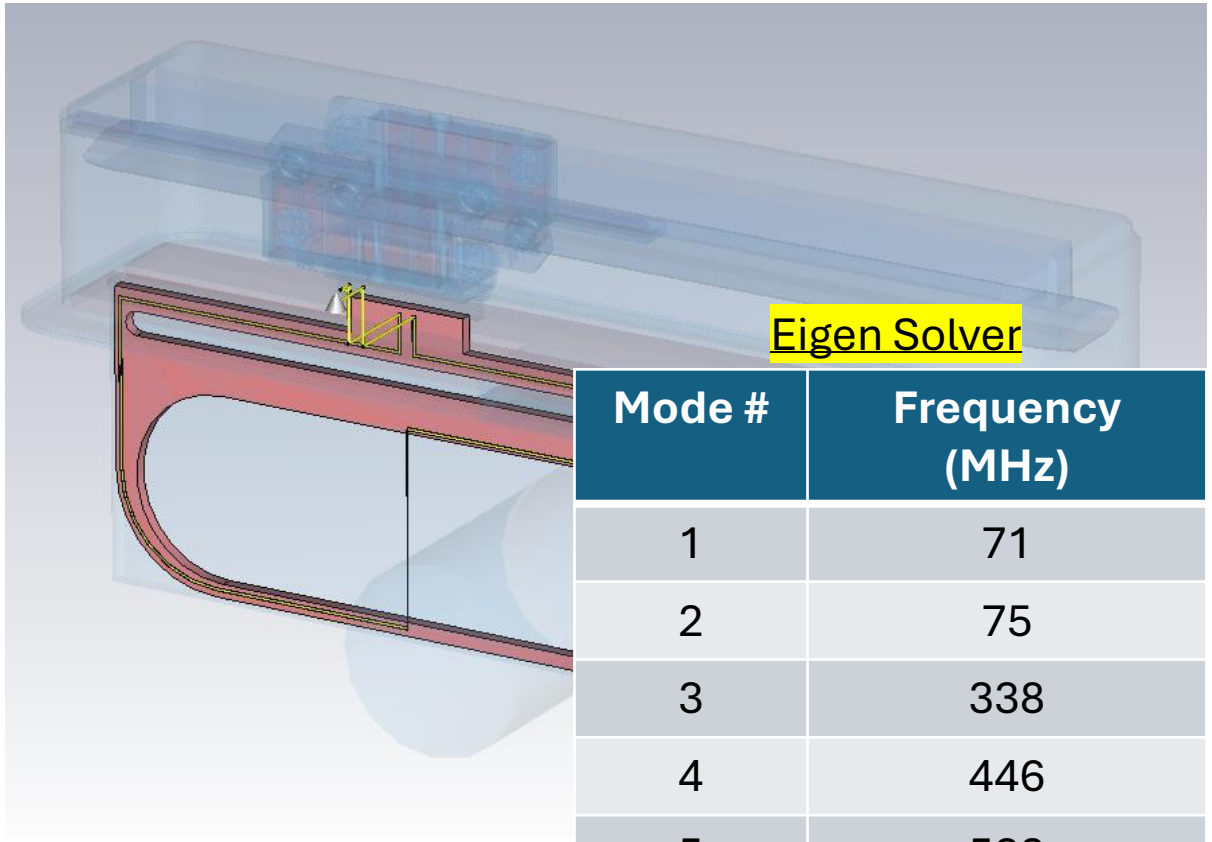
3





BWS Model Trial with Wire (1)

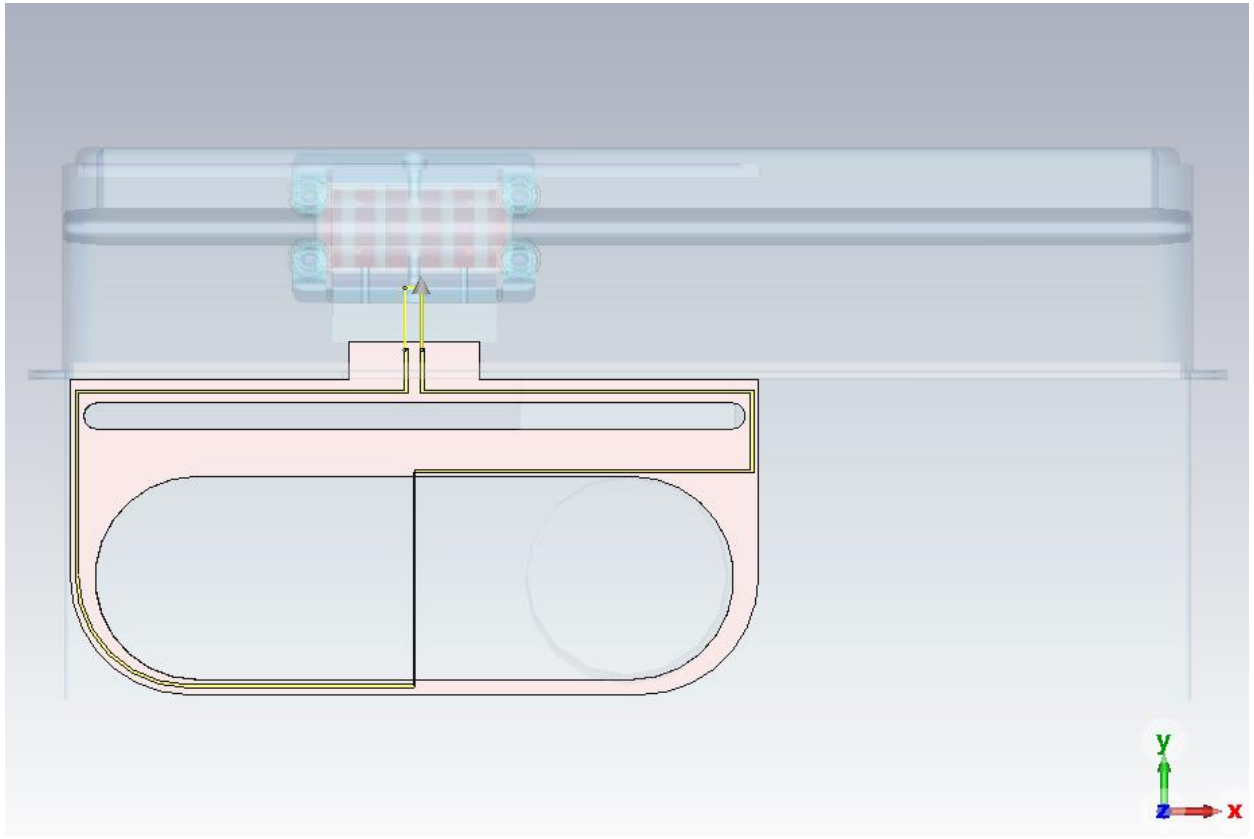
CST Model with Wire & Feedtrough



Eigen Solver

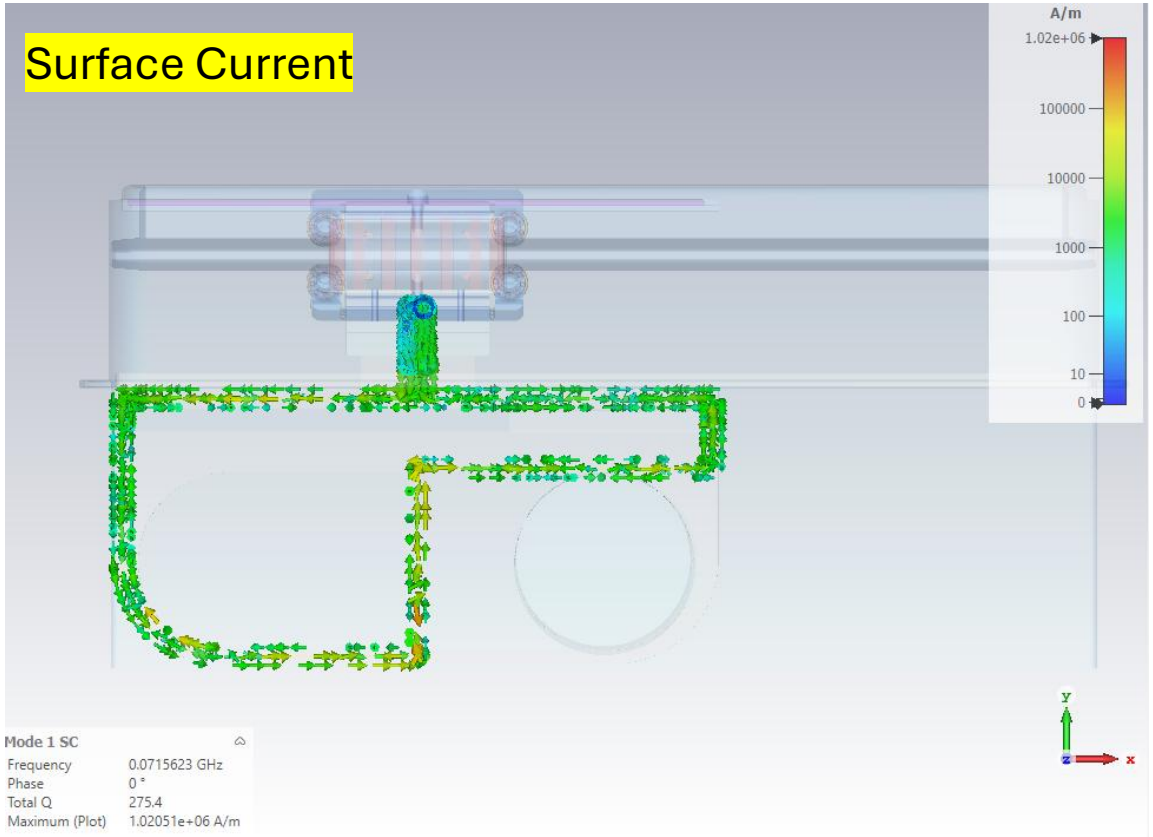
Mode #	Frequency (MHz)
1	71
2	75
3	338
4	446
5	532

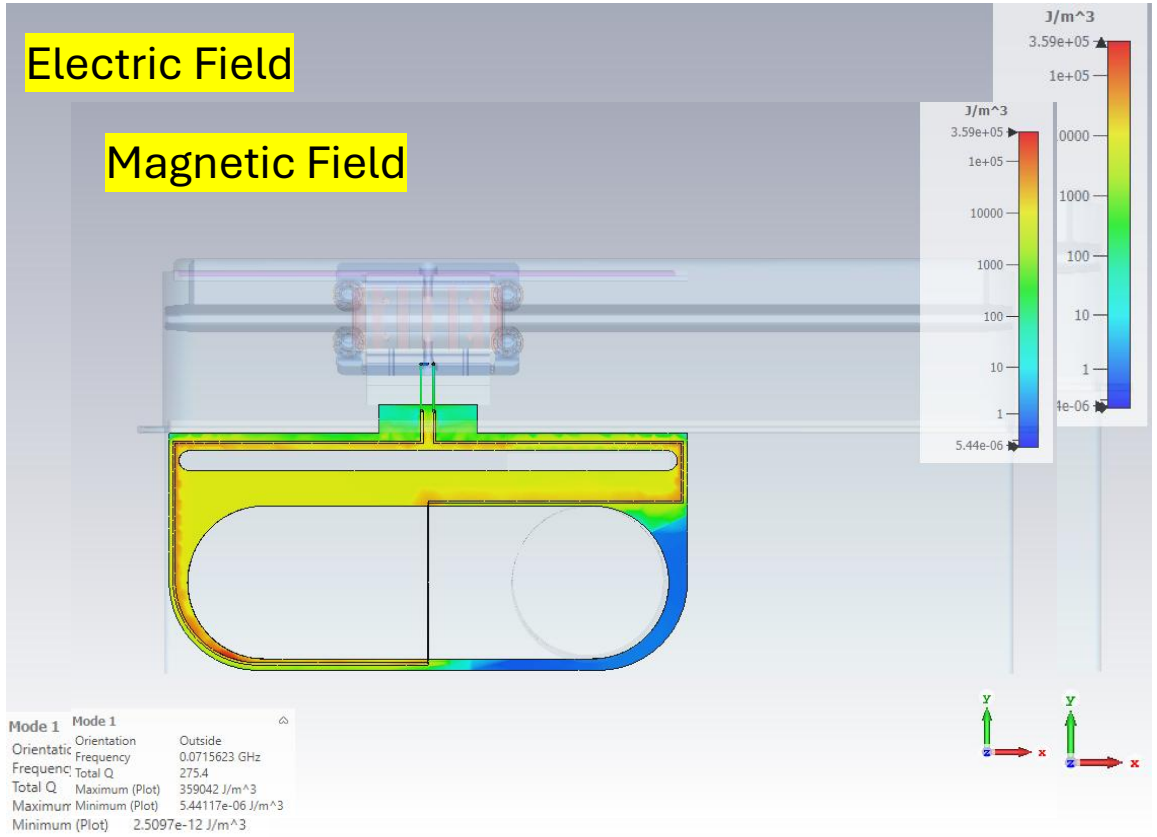
Front View



BWS Model Trial with Wire (2)

Mode #1 -> 71 MHz





BWS Model Trial with Wire (3)

Mode #5 –> 532 MHz