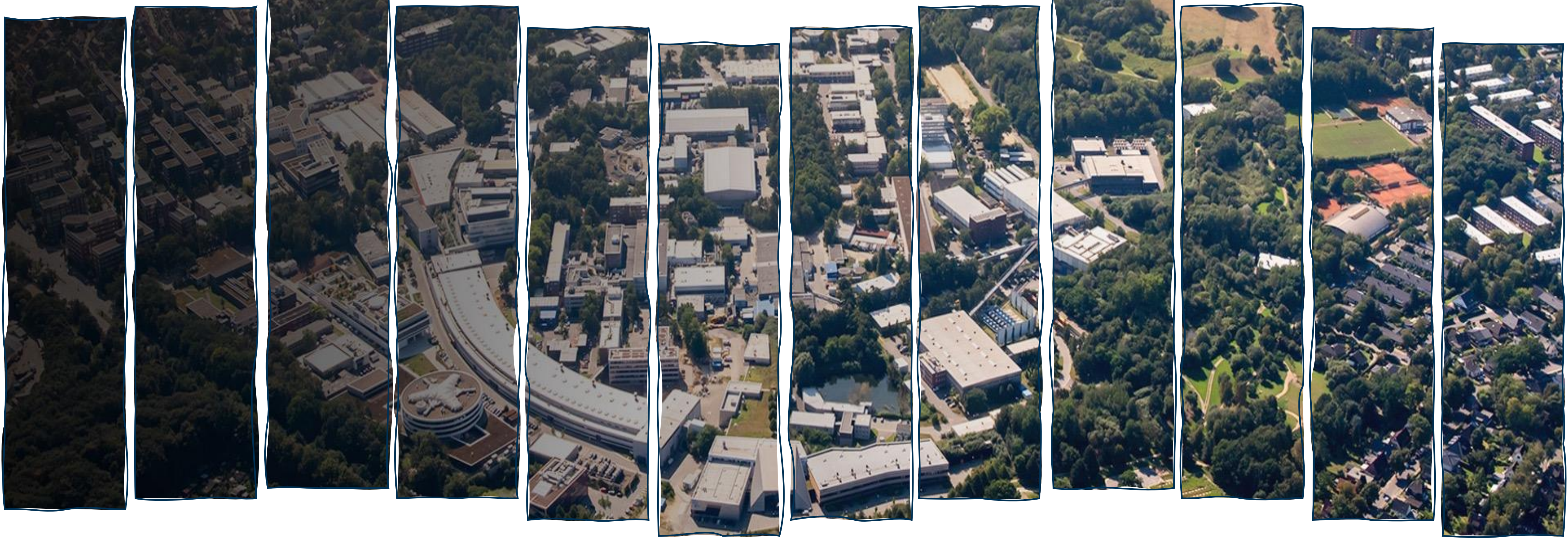


VACI Suite updates

FCC Booster and Main Ring optimization

Ali Rajabi

Hamburg, 13th June, 2024

Thanks to:
Rainer Wanzenberg (DESY), A Ghribi (CNRS), M. Migliorati (UniRoma)

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 951754

Table of content

Collective Effects and Instabilities

VACI Suite
Behind the scenes

However difficult life may seem, there is always something you can do and succeed at.

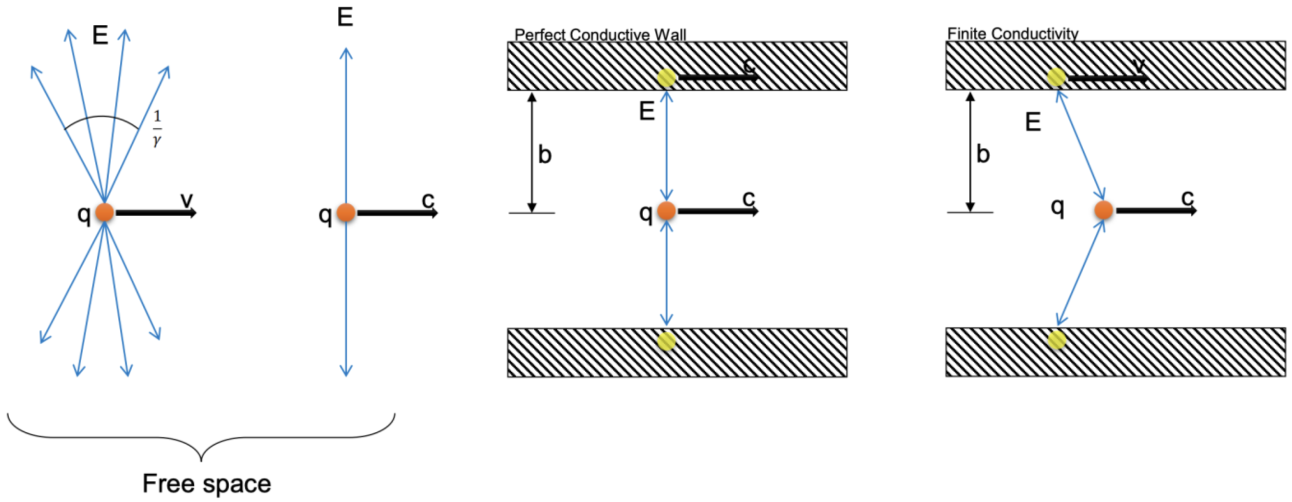
Stephen Hawking

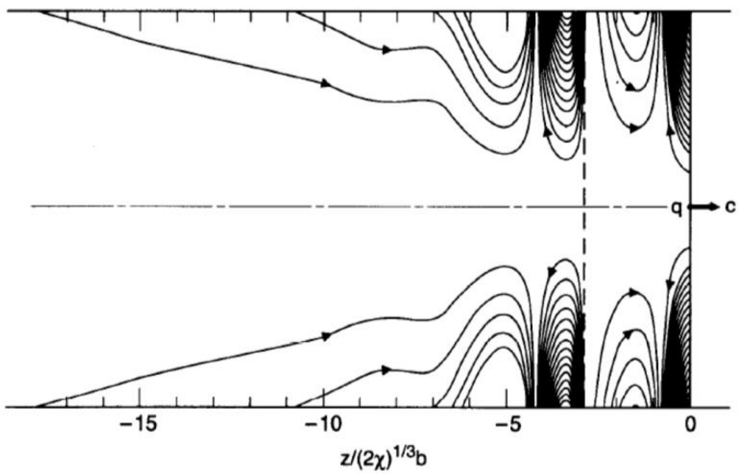
Introduction

What are collective effects?

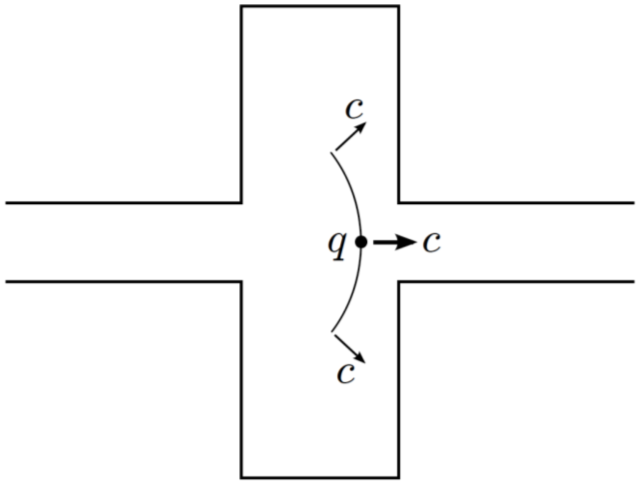
- Interactions between particles within a beam are generally known as collective effects

  1. Incoherent
     - ❖ Space-charge
     - ❖ Scattering
  2. Coherent
     - ❖ Wake-fields





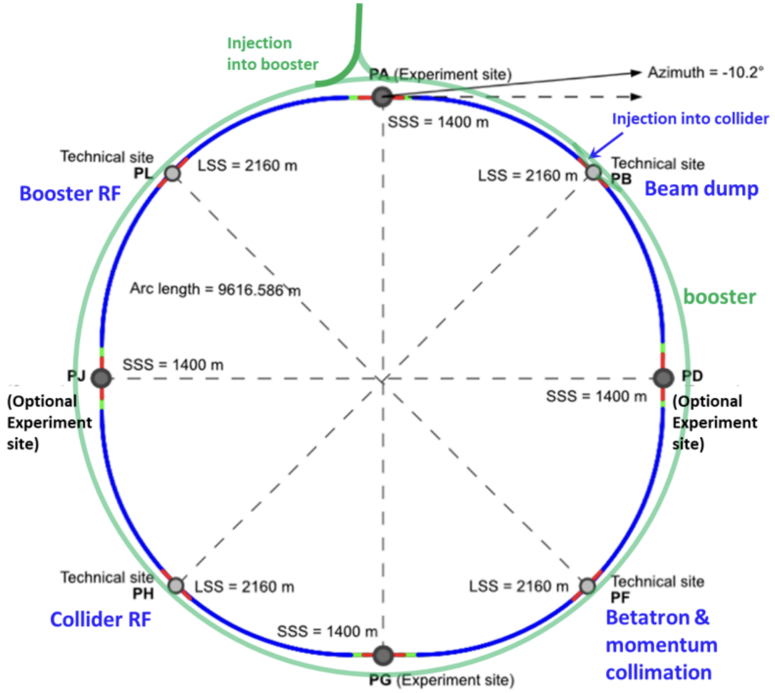
Wake fields following a point charge in a cylindrical beam pipe with resistive walls. (K. Bane)



Source of Impedance in the Ring

FCC Rings (old parameters, CDR)

- Beam pipes (Resistive Wall Impedance, ~90.7 km)
- RF Cavities (No. 48 in a 4-cell array)
- RF Cavity Tapers (No. 12 double tapers)
- Synchrotron Radiation Absorbers
- Collimators (No. 8)
- BPMs (No. 8000)
- Bellows (No. 12000)



Wake-field

Maxwell's equation

$$
\begin{aligned}
\mathrm{div}\vec{D} &= \rho_m, \\
\vec{\mathrm{curl}}\vec{H} - j\omega\vec{D} &= \vec{J}_m, \\
\vec{\mathrm{curl}}\vec{E} + j\omega\vec{B} &= 0, \\
\mathrm{div}\vec{B} &= 0,
\end{aligned}
$$

$$\rho(r,z;\omega) = J_z(r,z;\omega)$$

$$J_n = \frac{Q_n}{A}\,\sigma(r;\ a,b)e^{in\theta}e^{-iks}$$

where:

$\sigma(r;\ a,b)$ means particles are in a ring with a thicknes of (b−a)

A is the ring area

θ is the angle distribution of electrons around the ring

$\vec{E} = -\vec{\nabla}\varphi - \frac{\partial}{\partial t}\vec{A}$ And $\vec{B} = \vec{\nabla}\times\vec{A}$

$\vec{\nabla}.\vec{A} = 0$ Coulomb gauge

$\partial_t \Rightarrow -i\omega$ Fourier Transform

$\partial_z \Rightarrow -i\omega/v$ Long pipe Appr.

Boundary Condition

$$
\begin{cases}
\vec{\nabla}.\left(\varepsilon\vec{\nabla}\varphi\right) = \rho_m \\
\vec{\nabla}\times\left({}^{1}/_{\mu}\,\vec{\nabla}\times\vec{A}\right) - \varepsilon\omega^2\vec{A} = -J_n\hat{e}_z + i\varepsilon\omega\vec{\nabla}\varphi
\end{cases}
$$

Resistive wall wake-field

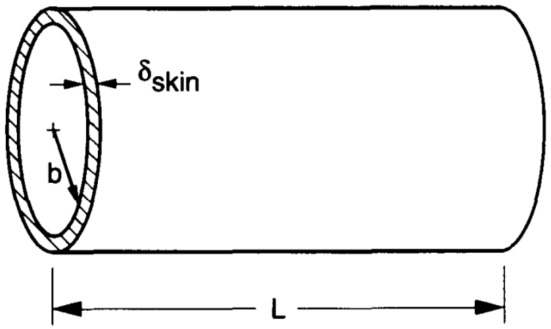
Simple Geometries

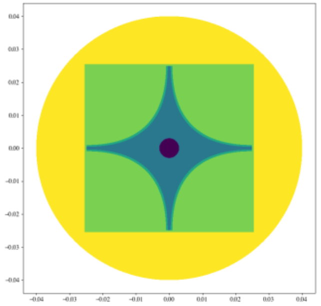
$$E_s = -\frac{16q}{4\pi\varepsilon_0 b^2}\left(\frac{e^u}{3}\cos(\sqrt{3}u) - \frac{\sqrt{2}}{\pi}\int_0^\infty \frac{x^2 e^{ux^2}}{x^6+8}\,dx\right), \qquad (14.114)$$

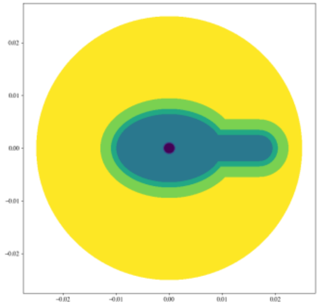
$$E_r = cB_\theta = \frac{8qr}{4\pi\varepsilon_0 b^3 \xi^{2/3}} \times \left(\frac{e^u}{3}\cos(\sqrt{3}u) - \frac{e^u}{\sqrt{3}}\sin(\sqrt{3}u) - \frac{\sqrt{2}}{\pi}\int_0^\infty \frac{x^4 e^{ux^2}}{x^6+8}\,dx\right), \qquad (14.115)$$

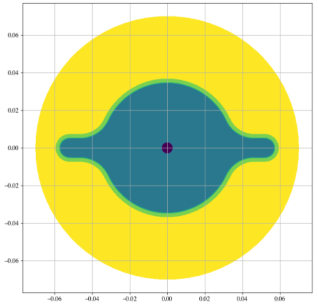
where:

$$u = \frac{z}{b\xi^{2/3}}. \qquad (14.116)$$





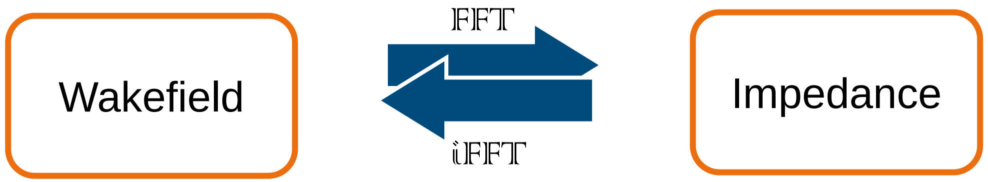




Wolski, A. (2023). Beam Dynamics in High Energy Particle Accelerators 2nd Edition

Resistive wall wake-field

How to calculate impedance



Based on: *Robert L. Gluckstern and Uwe Niedermayer*

$$\underline{\vec{Z}}(\vec{r}_1^{\perp}, \vec{r}_2^{\perp}, \omega) = -\int_{-\infty}^{\infty} \vec{W}(\vec{r}_1^{\perp}, \vec{r}_2^{\perp}, s) e^{-i\omega s/v} \frac{\mathrm{d}s}{v}.$$

Single particle

$$\underline{\vec{Z}}(\vec{r}_1^{\perp}, \vec{r}_2^{\perp}, \omega) = -\frac{1}{q_1 q_2} \int_{-\infty}^{\infty} \underline{\vec{F}}(\vec{r}_1^{\perp}, \vec{r}_2^{\perp}, z, \omega) e^{+i\omega z/v} \mathrm{d}z,$$

one should note that the integral is not a Fourier transform, but the wake integration in the frequency domain.

$$\left\{ \begin{aligned} &\vec{J}_s(\vec{r}_\perp, z, t) = q_1 \sigma(\vec{r}_\perp) \delta(z - vt) \vec{v} \\ &\underline{\vec{J}}_s(\vec{r}_\perp, z, \omega) = q_1 \sigma(\vec{r}_\perp) e^{-i\omega z/v} \vec{e}_z. \end{aligned} \right\}$$

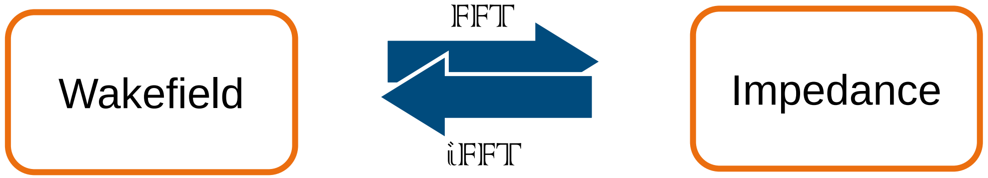
Integrating over the beam in FD
Like Convolution in TD

$$\underline{\vec{Z}}(\omega, \vec{r}_2^{\perp}) = -\frac{1}{q_1 q_2} \int_{\text{beam}} \underline{\vec{F}}(\vec{r}_1^{\perp}, \vec{r}_2^{\perp}, z, \omega) e^{i\omega z/v} \sigma(\vec{r}_1^{\perp}) \mathrm{d}r_1^{\perp} \mathrm{d}z.$$

$$\underline{Z}_{\|}(\omega) = -\frac{1}{q^2} \int_{\text{beam}} \underline{\vec{E}} \cdot \underline{\vec{J}}_s^{*} \mathrm{d}V.$$

Resistive wall wake-field

How to calculate impedance



Based on: *Elias Métral*

- *Non axis-symmetric structures:*
  - *A current density with some azimuthal Fourier component may create an electromagnetic field with various different azimuthal Fourier components*
    - ✓ *A more general beam coupling impedance is REQUIRED to treat coupling of different azimuthal Fourier components*

$$Z_{m,n}(\omega) = \int dv\, E_m * J_n^*$$ over the beam area

$$J_n = \frac{Q}{2\pi a^{|n|+1}} \delta(r-a)\, e^{jn\vartheta}\, e^{-jks}$$ and $m, n = 0, \pm 1, \pm 2, \ldots$

Considering $m \geq 0$ instead of $m = 0, \pm 1, \pm 2, \ldots$:

$$\left.\begin{aligned} \bar{J}_m &= J_m + J_{-m} \\ \bar{E}_m &= E_m + E_{-m} \end{aligned}\right\} \Rightarrow \bar{Z}_m(\omega) = -\frac{1}{Q^2} \int dV \left(E_m + E_{-m}\right)\left(J_m^* + J_{-m}^*\right)$$

$$\begin{cases} \text{For } m = 0: & \bar{Z}_0 = Z_{0,0} \\ \text{For } m \geq 1: & \bar{Z}_m = Z_{m,m} + Z_{m,-m} + Z_{-m,m} + Z_{-m,-m} \end{cases}$$

Resistive wall wake-field

How to calculate impedance

Based on: *Robert L. Gluckstern, Elias Métral, and Uwe Niedermayer*

$$Z_\perp = A(z) + x_1 Z_\perp^{dip} + x_2 Z_\perp^{det}$$

Applying Panofksy-Wenzel theorem:

$$kZ_m^\perp = \nabla_w^\perp Z_m^\parallel$$

$$k\,Z_x = \left(Z_{0,1} + Z_{0,-1}\right) + x_1 \bar{Z}_x + j\,y_1\left(-Z_{1,-1} - Z_{1,1} + Z_{-1,-1} + Z_{-1,1}\right) + 2\left(Z_{0,2} + Z_{0,-2}\right) x_2 + 2\left(Z_{0,2} - Z_{0,-2}\right) j\,y_2$$

$$k\,Z_y = j\left(Z_{0,1} - Z_{0,-1}\right) + y_1 \bar{Z}_y + j\,x_1\left(-Z_{1,-1} + Z_{1,1} - Z_{-1,-1} + Z_{-1,1}\right) - 2\left(Z_{0,2} + Z_{0,-2}\right) y_2 + 2\left(Z_{0,2} - Z_{0,-2}\right) j\,x_2$$

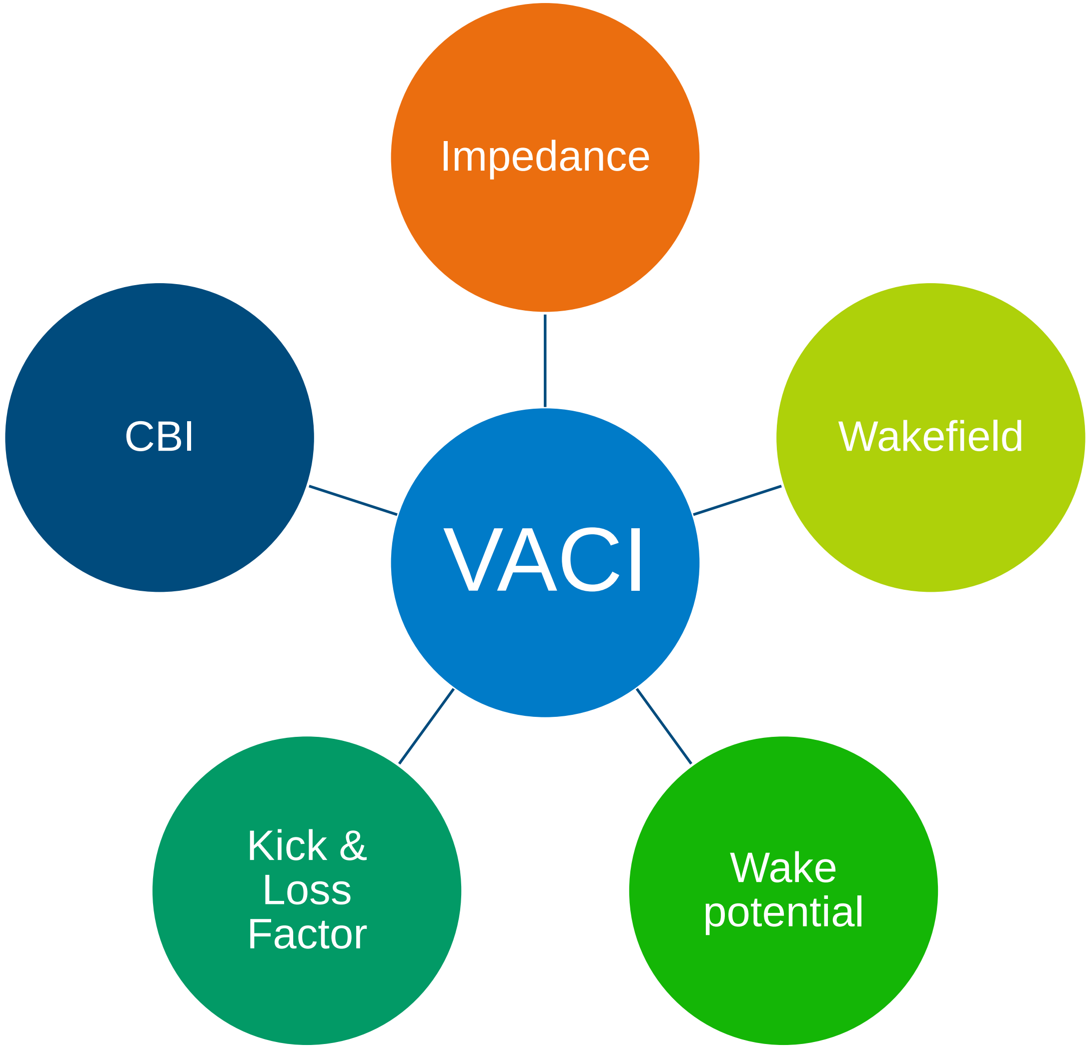
$$Z_x^{\text{driving}} = \bar{Z}_x / k \qquad Z_y^{\text{driving}} = \bar{Z}_y / k \qquad Z^{\text{detuning}} = -2\left(Z_{0,2} + Z_{0,-2}\right) / k$$

VACI Suite

A versatile tool for calculating the RW impedance in arbitrary pipe cross-sections

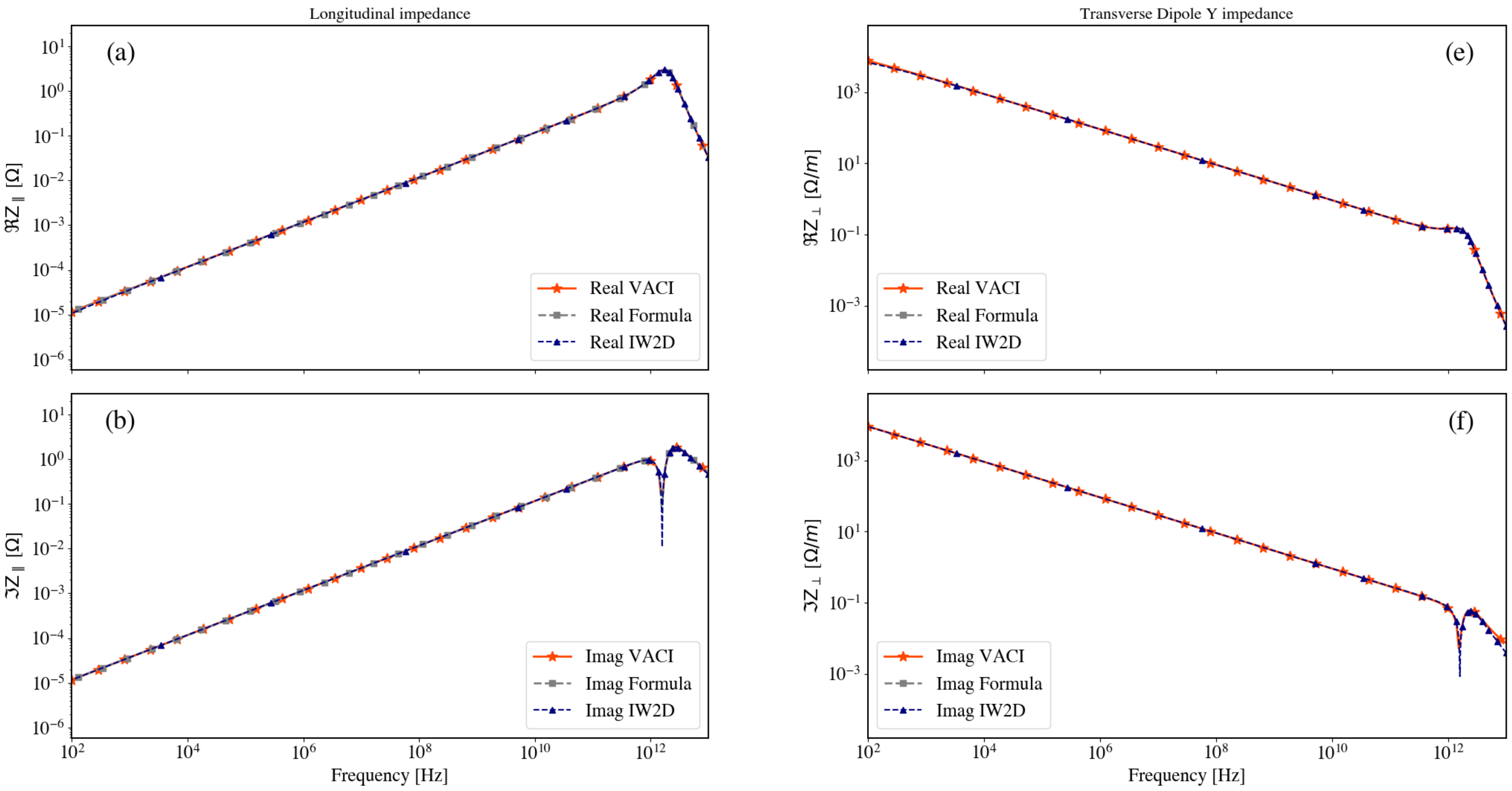
VACI Suite

Finite Element PDE solver



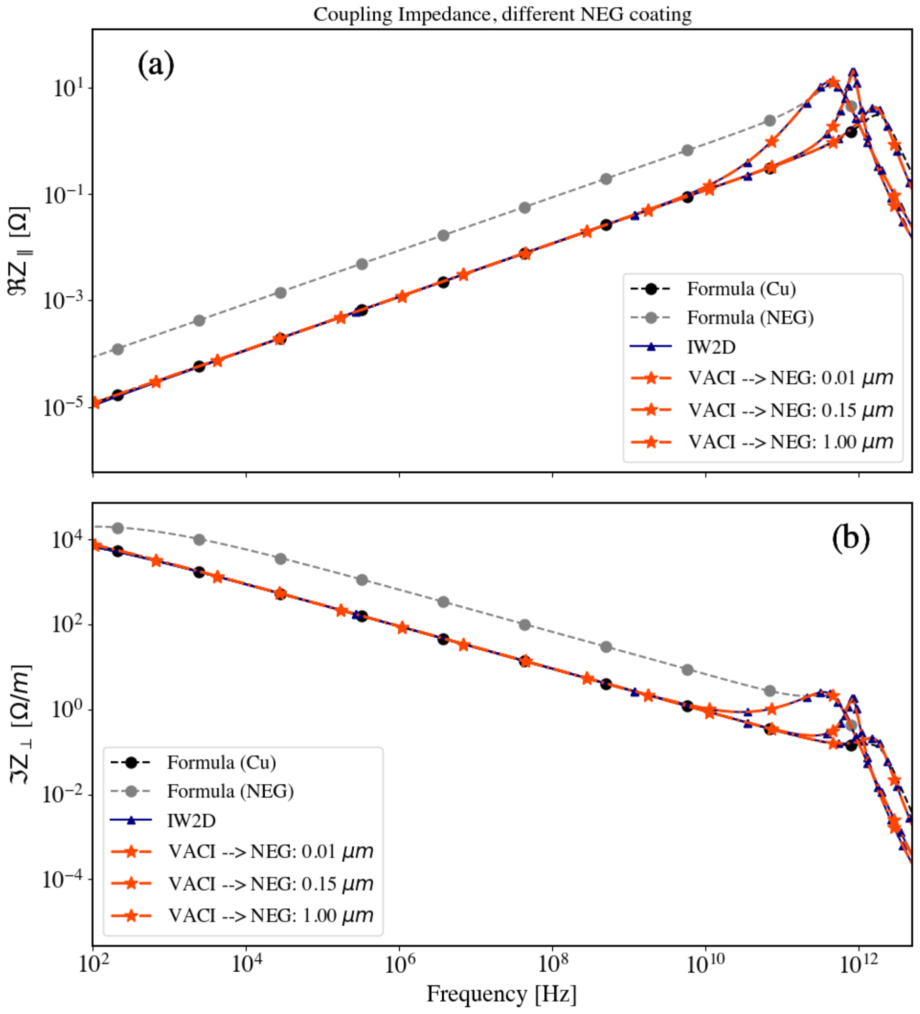
Round pipe

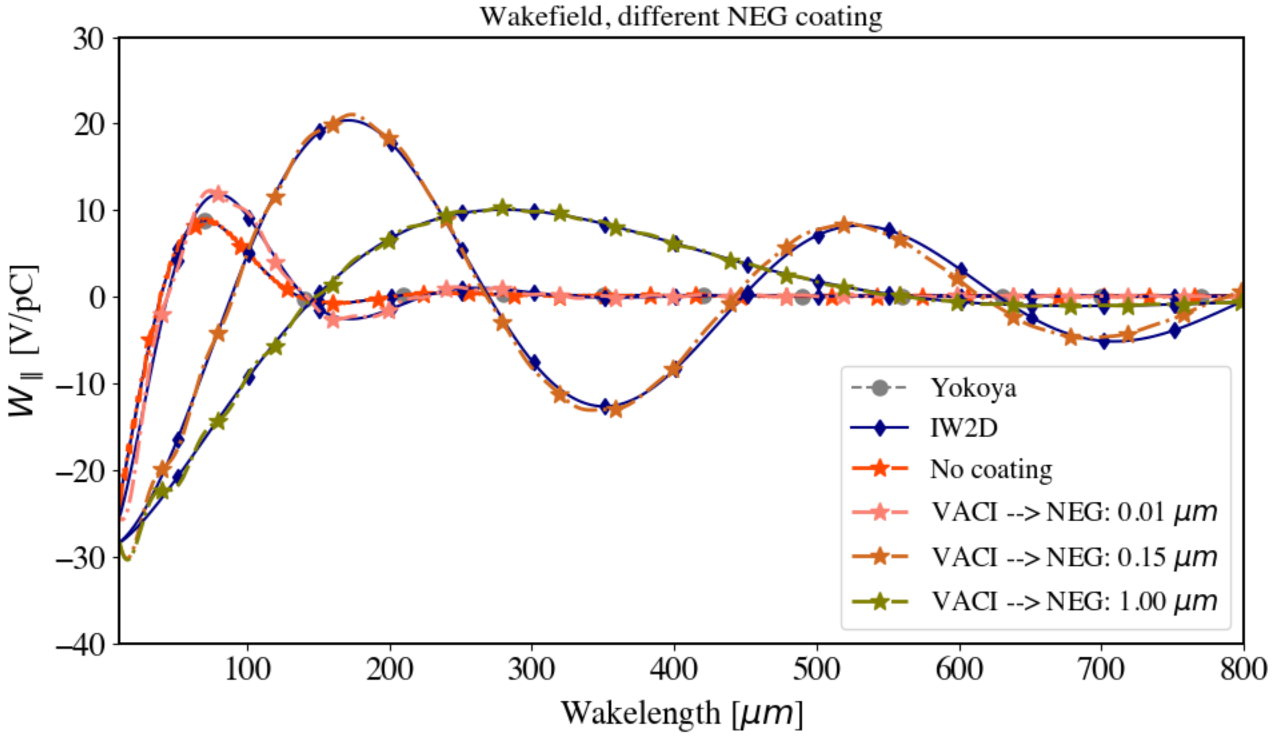
Impedance



MultiLayer Pipes

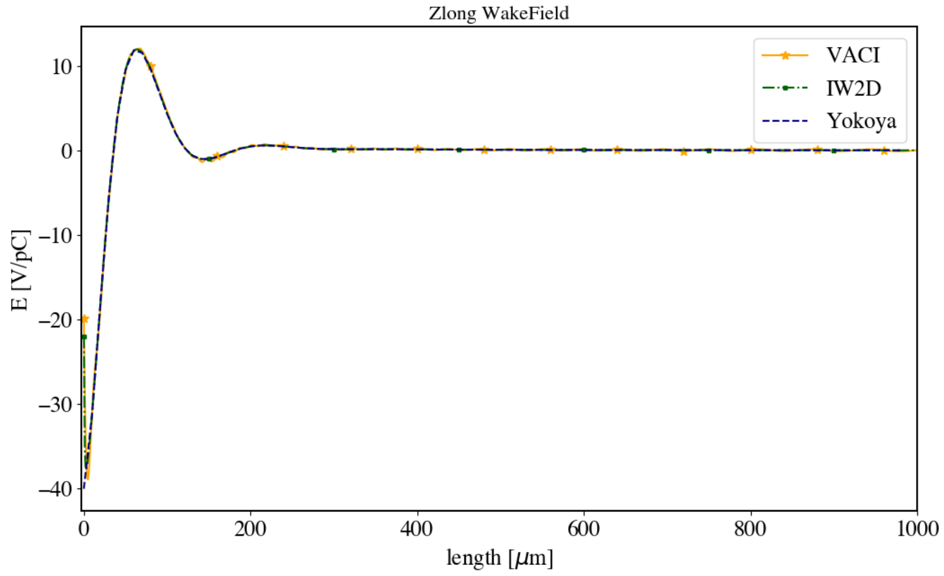
NEG coating

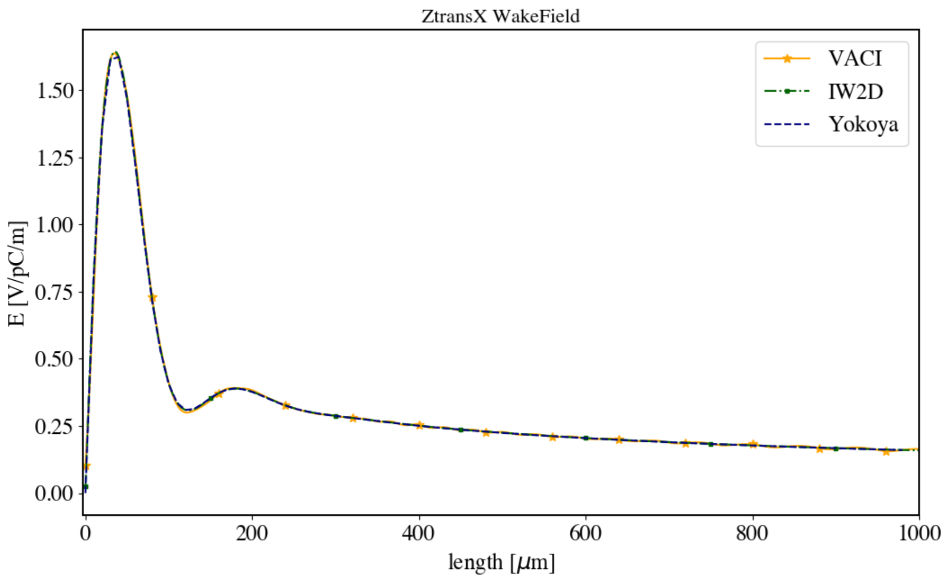


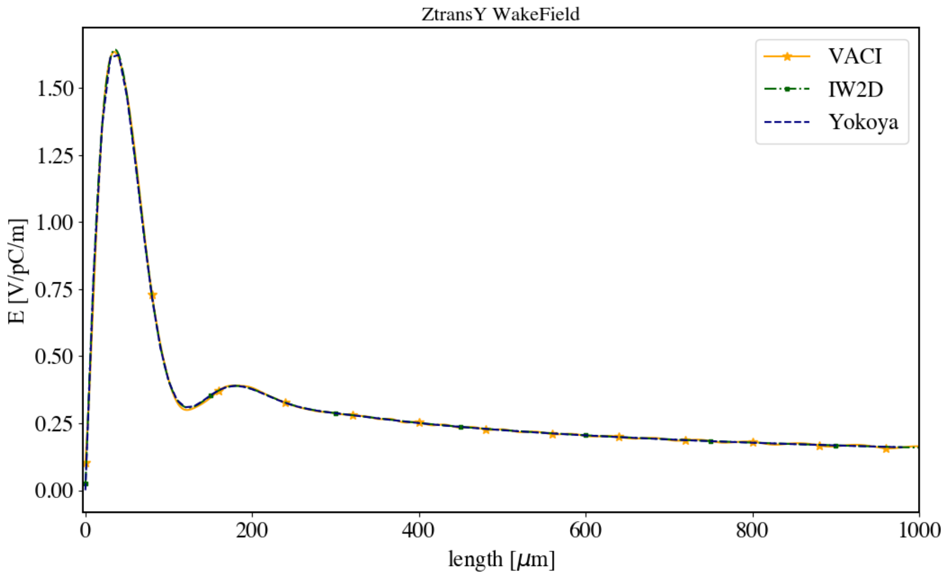


Round pipe

Wakefield, Green Function

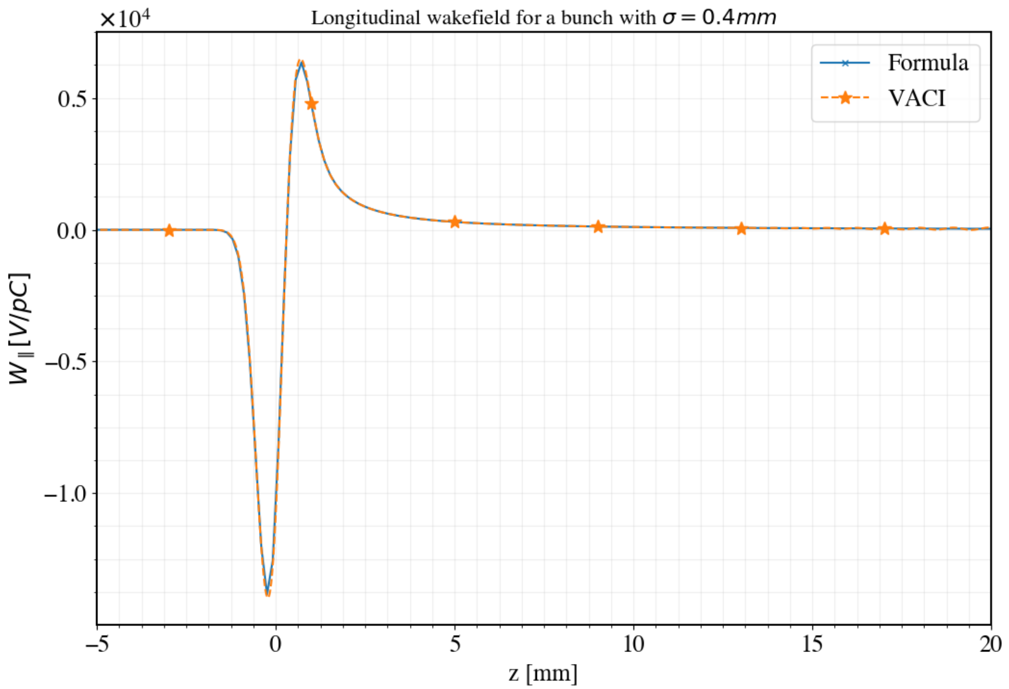


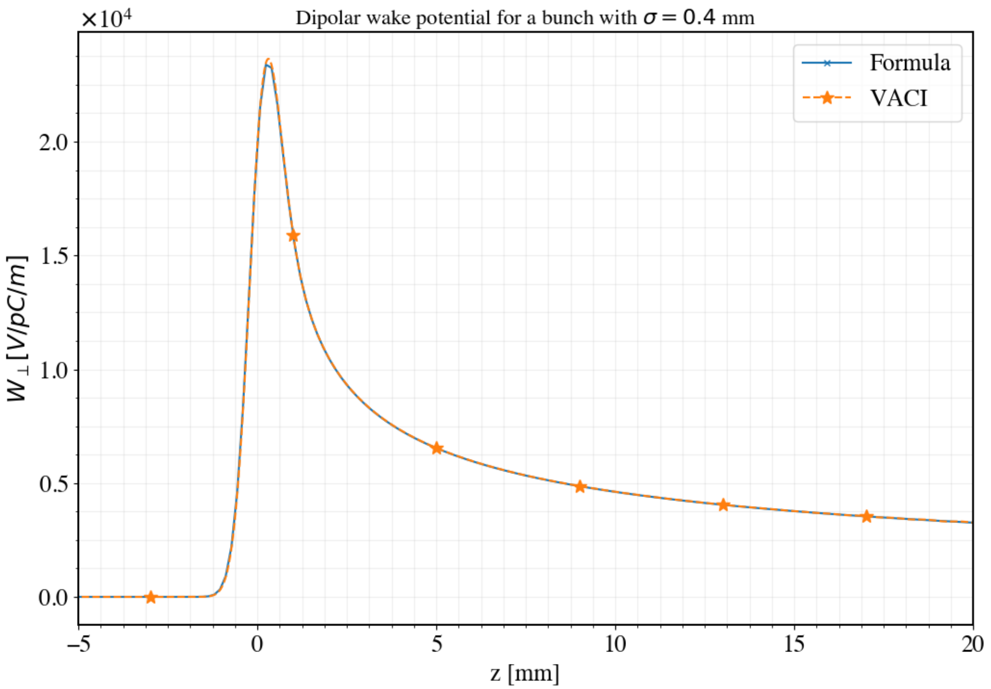




Round pipe

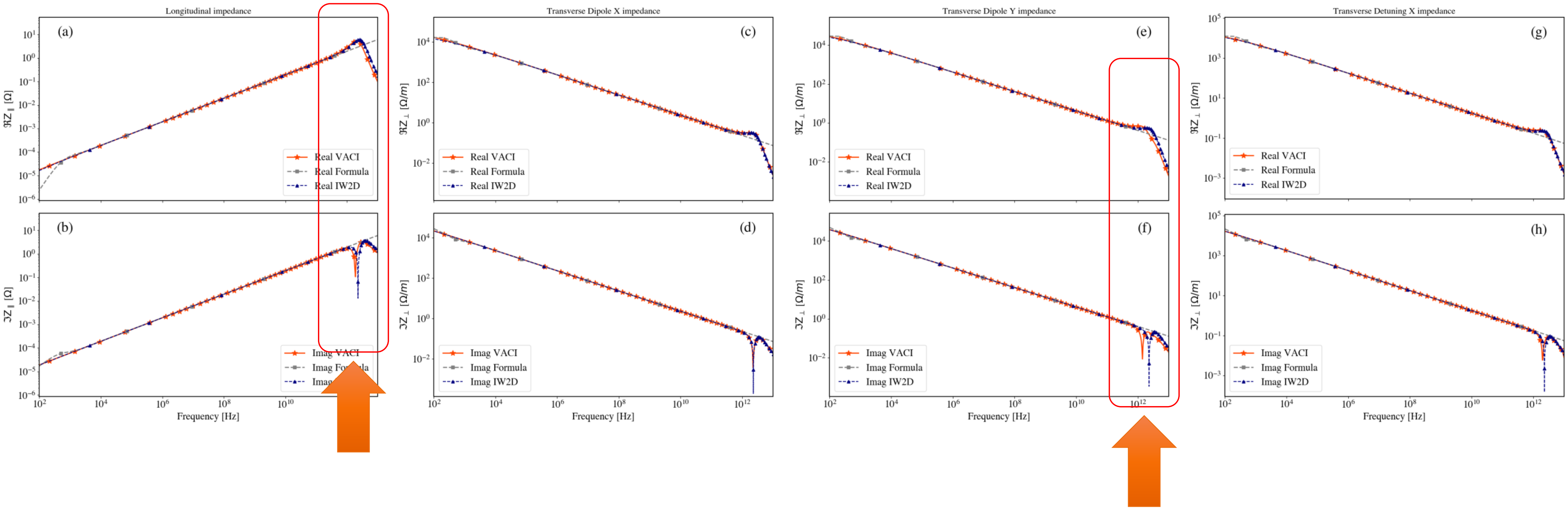
WakePotential $\sigma = 0.4\ mm$





Elliptical pipe

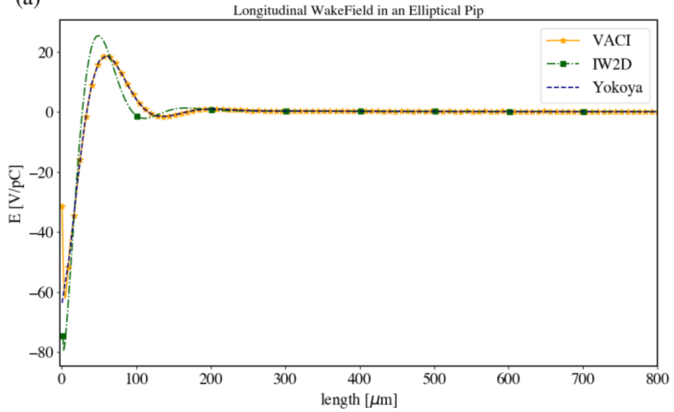
Compare with IW2D and Analytical Formula



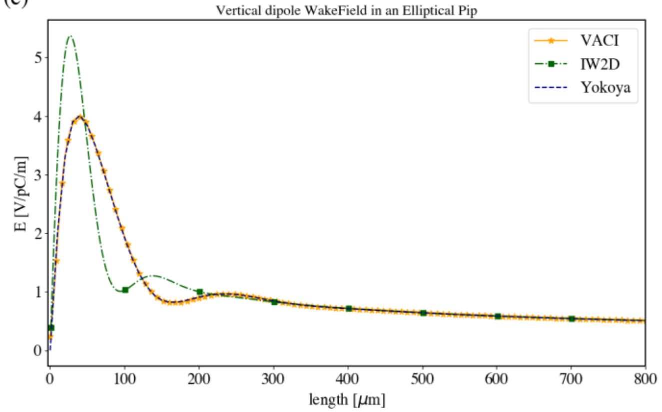
Elliptical pipe

Compare to IW2D and Yokoya’s Code

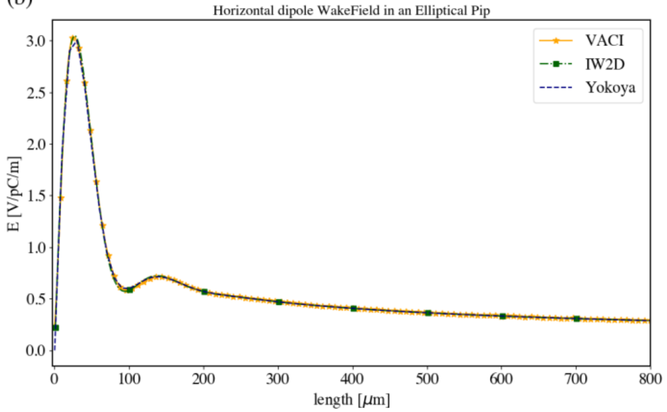
(a)



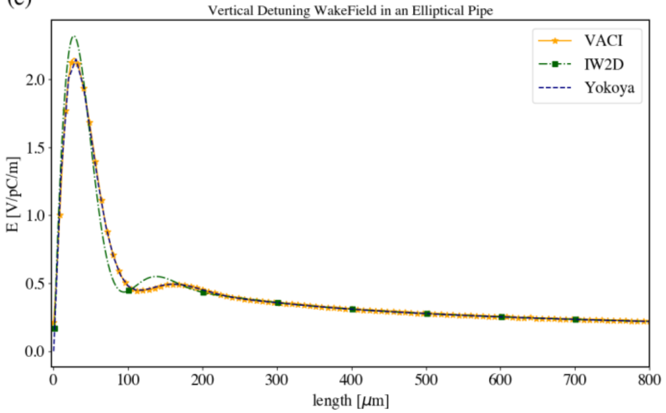
(c)



(b)



(e)



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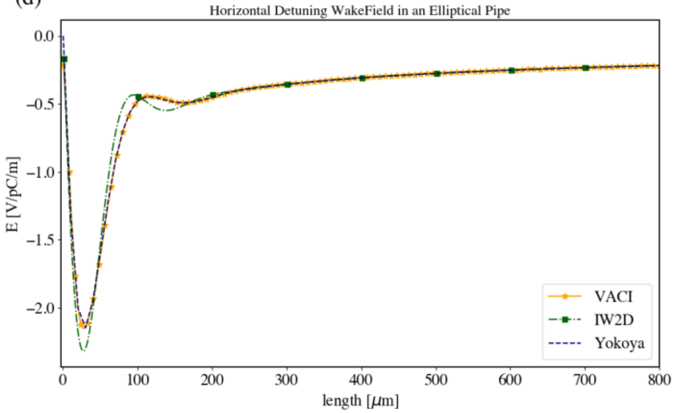


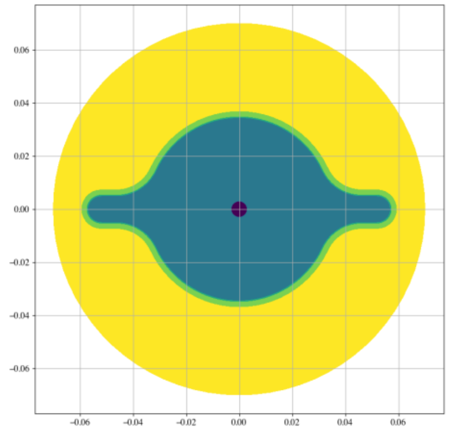
FCC Main Ring

- Round pipe with Winglets

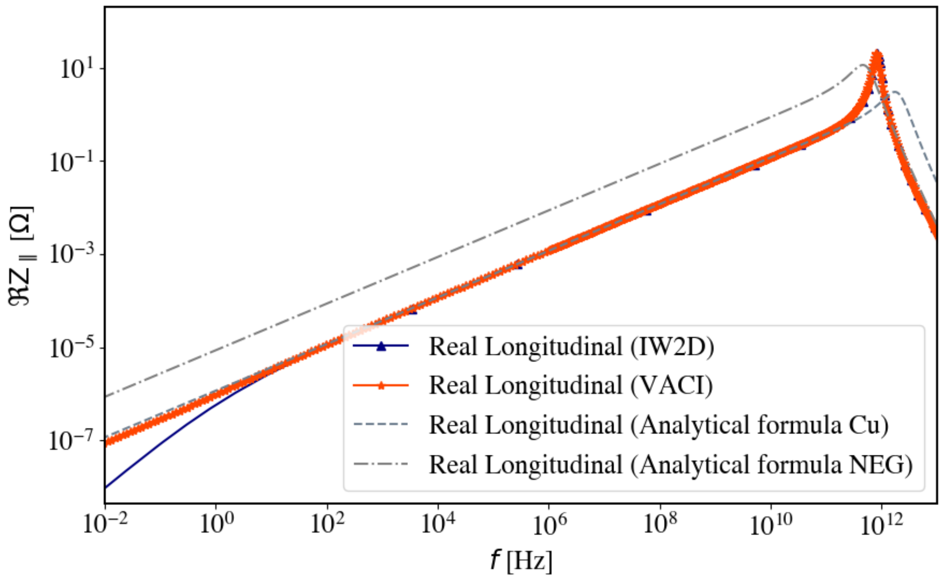
FCC main Ring

Monopolar Impedance

E -> 45.6 GeV
Pipe -> Cu (5.96e7 S/m)
NEG -> 1e6 (S/m)
R -> 35 mm



(a)



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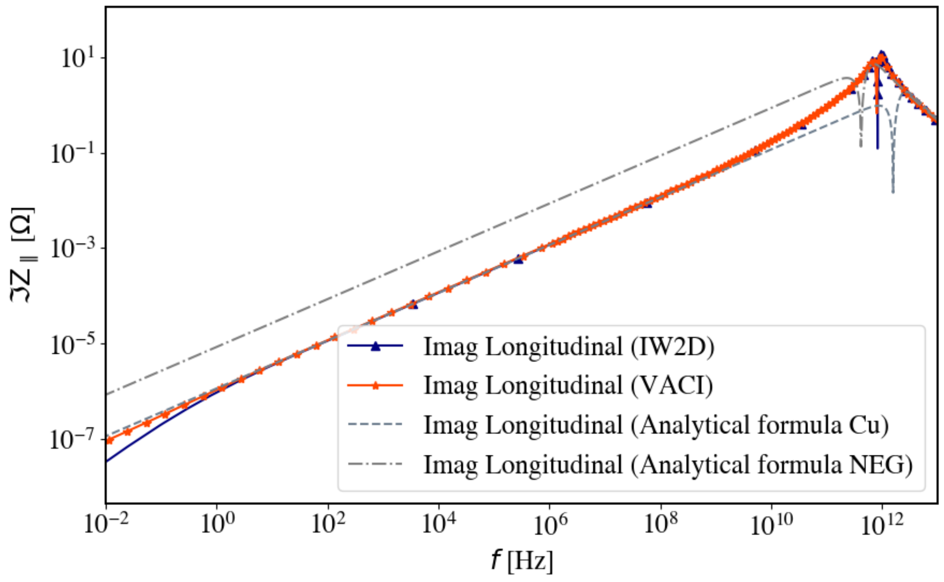
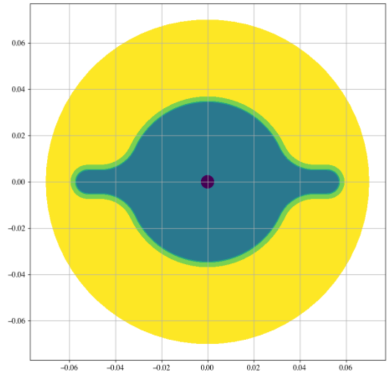
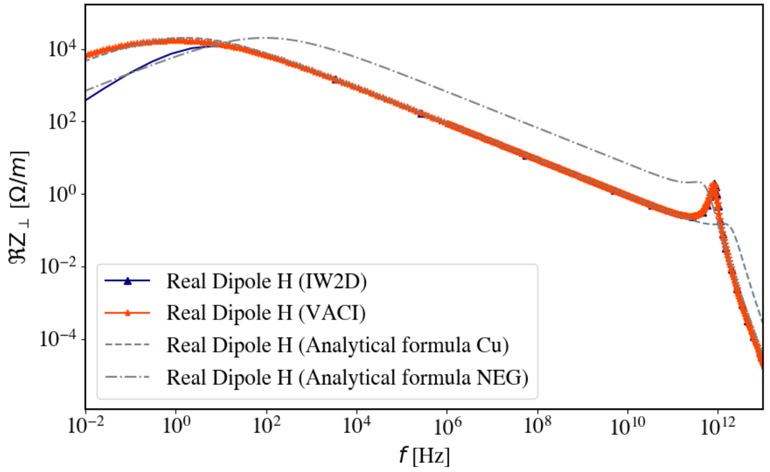


FCC main Ring

Dipolar Impedance



(a)



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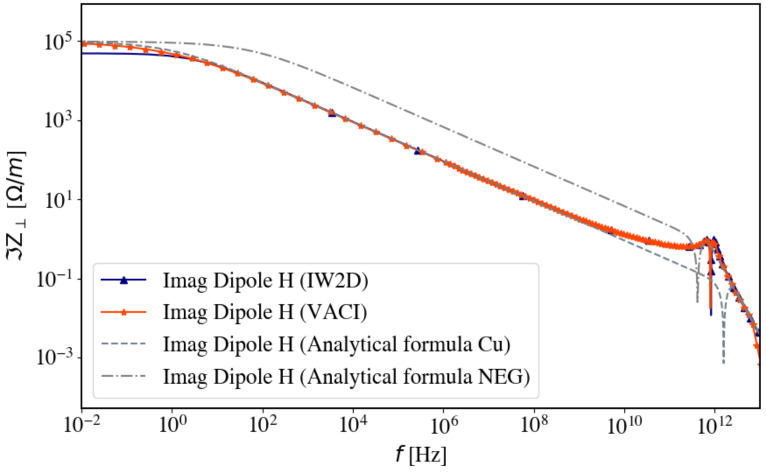
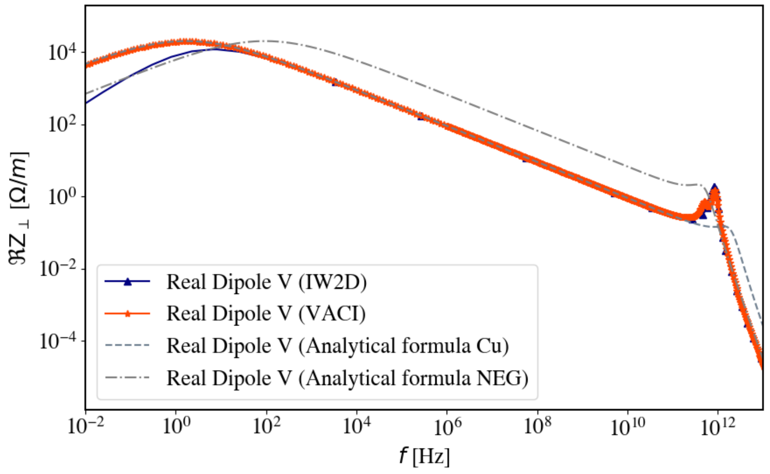


(a)



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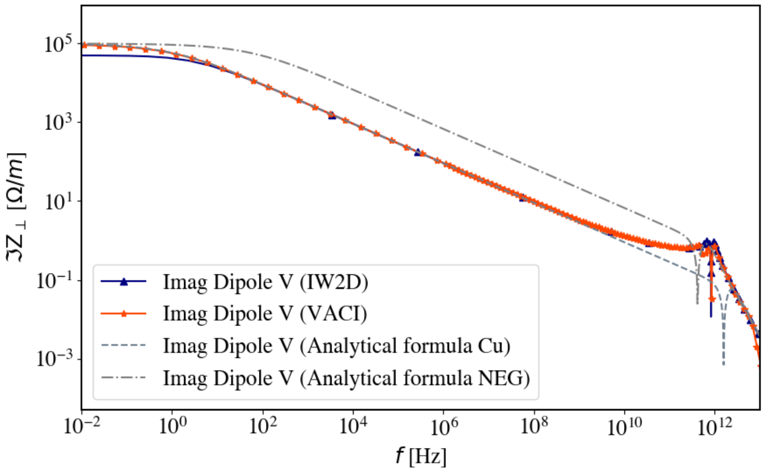
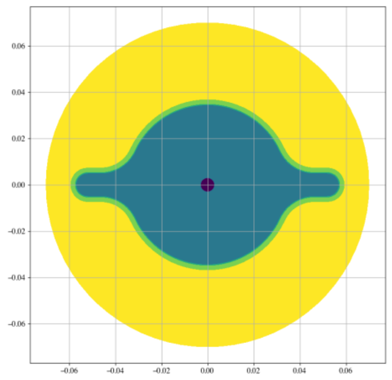
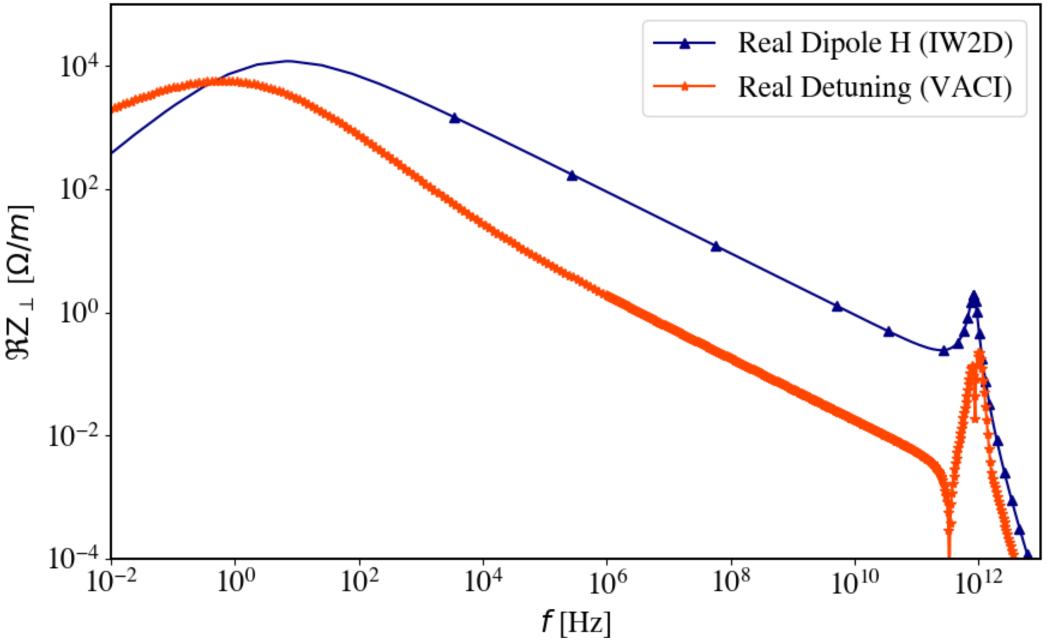


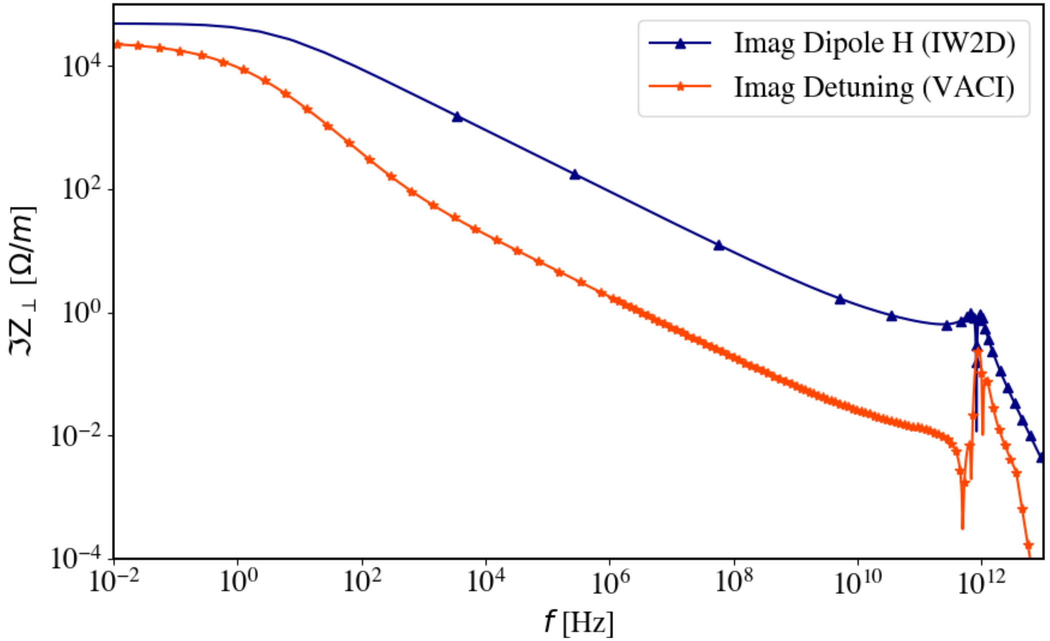
FCC main Ring

Detuning Impedance



$$W_x = A(z) + x_s W_x^{dip} + x_w W_x^{det}$$

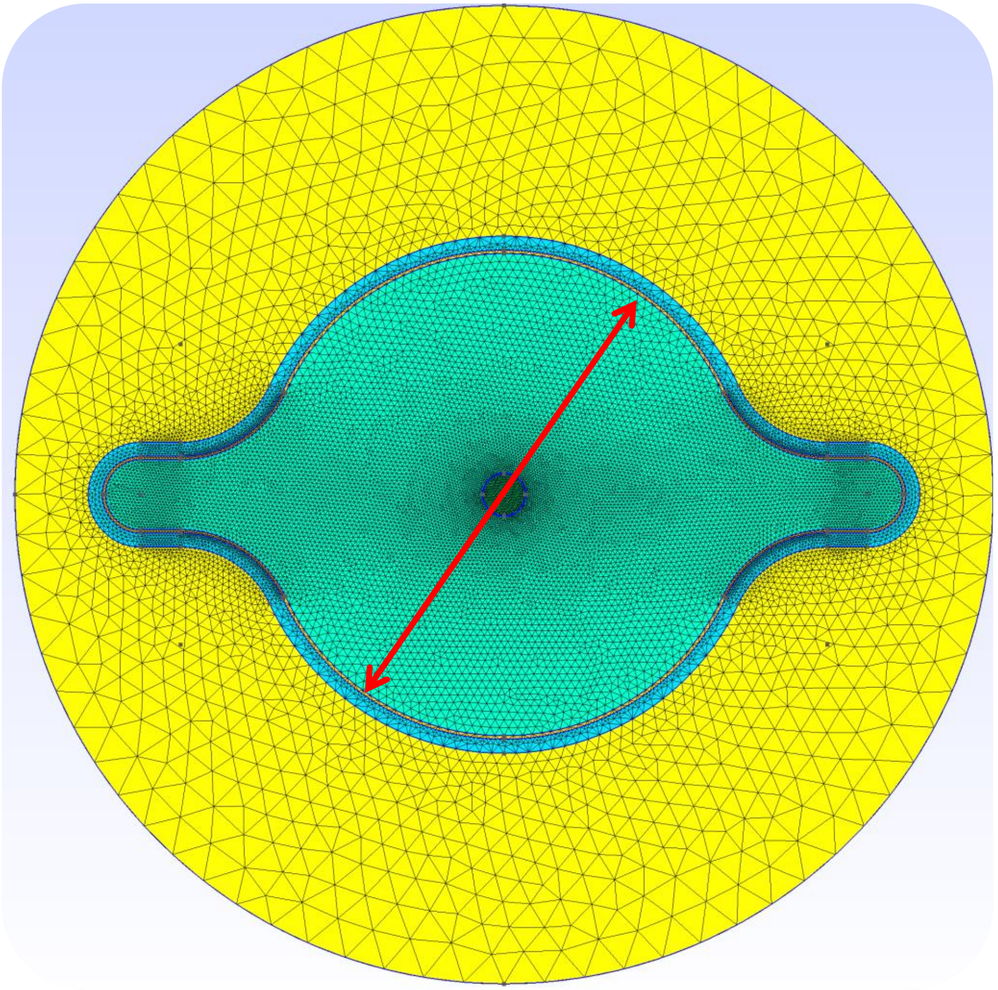




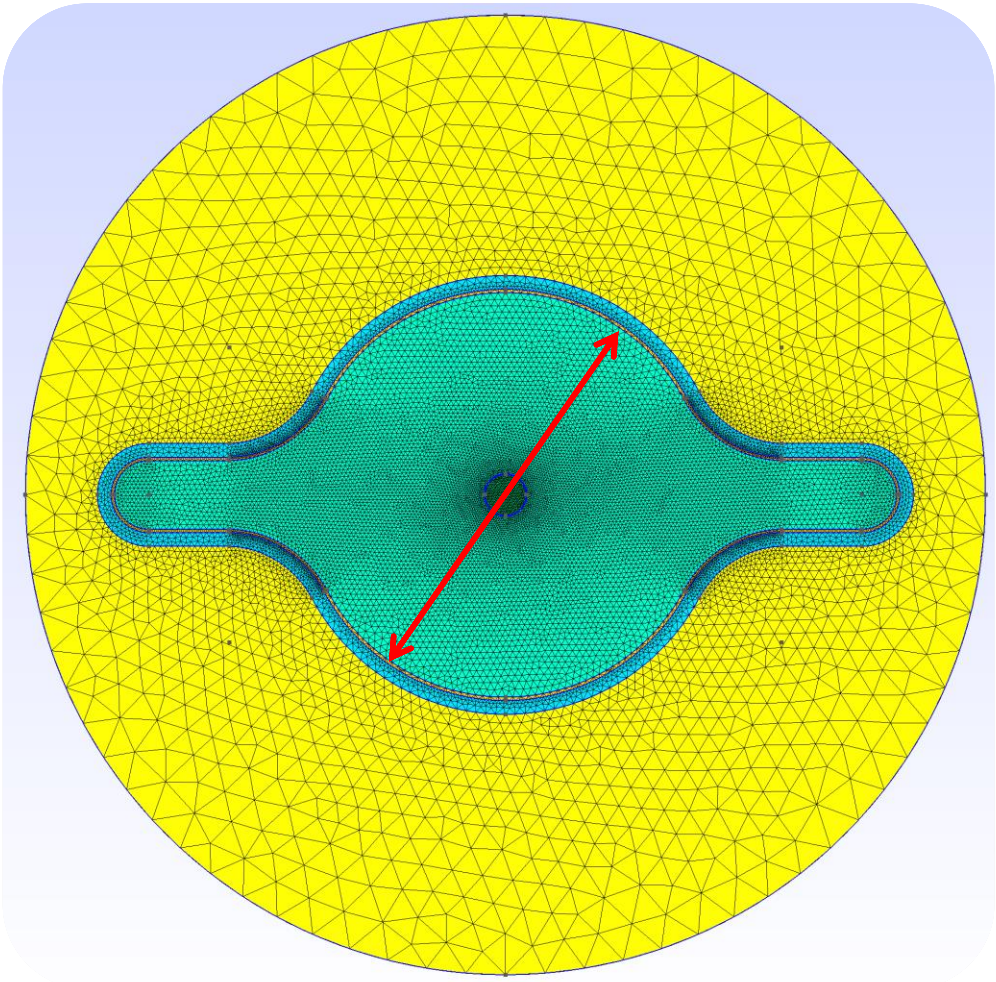
FCC main Ring

Changing Radius

35 mm

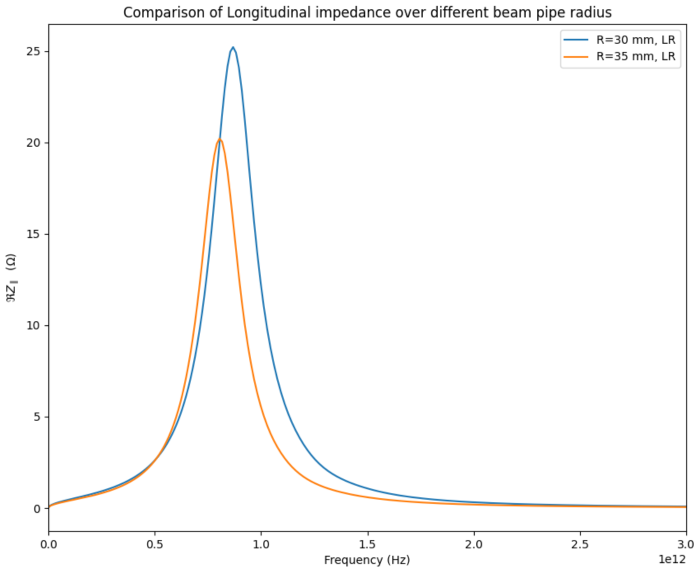


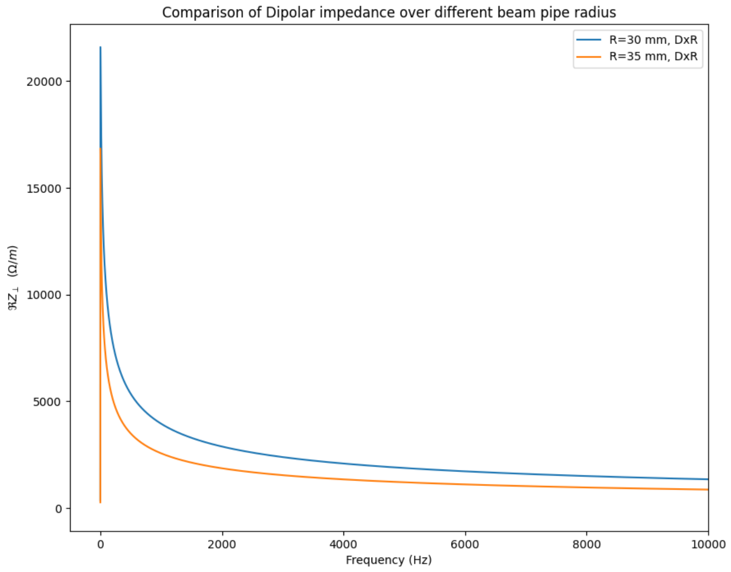
30 mm

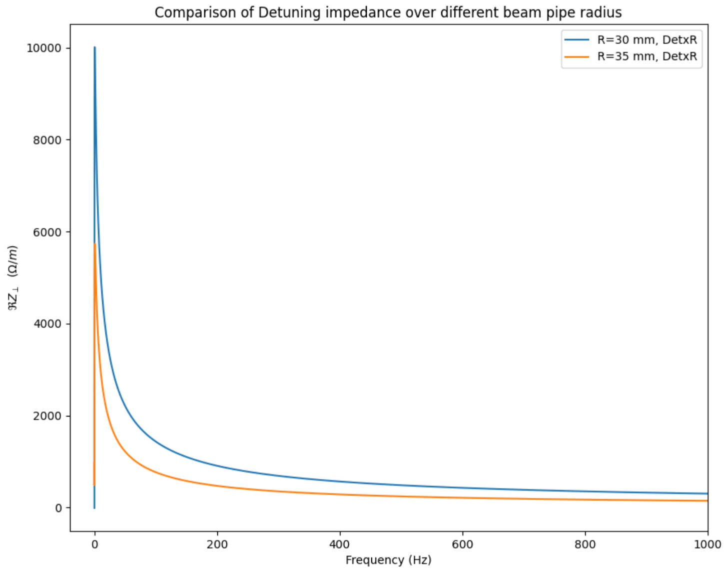


FCC main Ring

Changing Radius

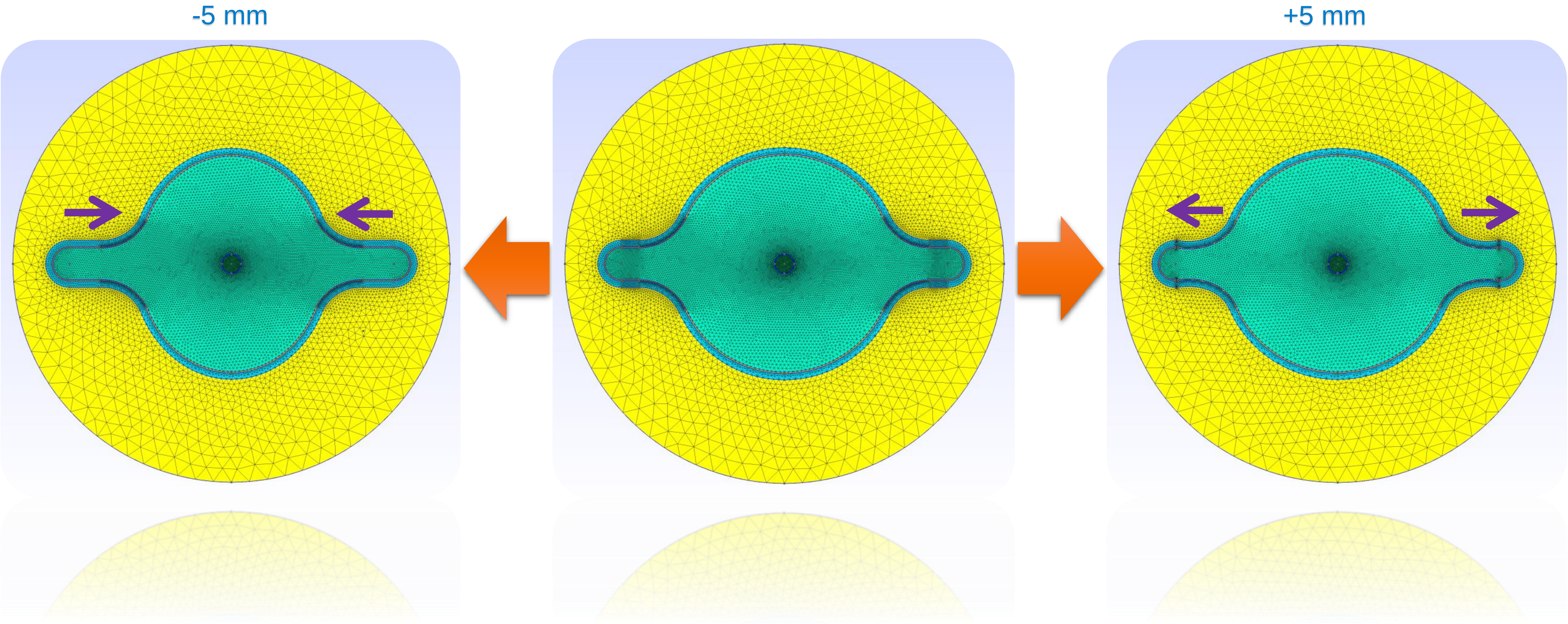






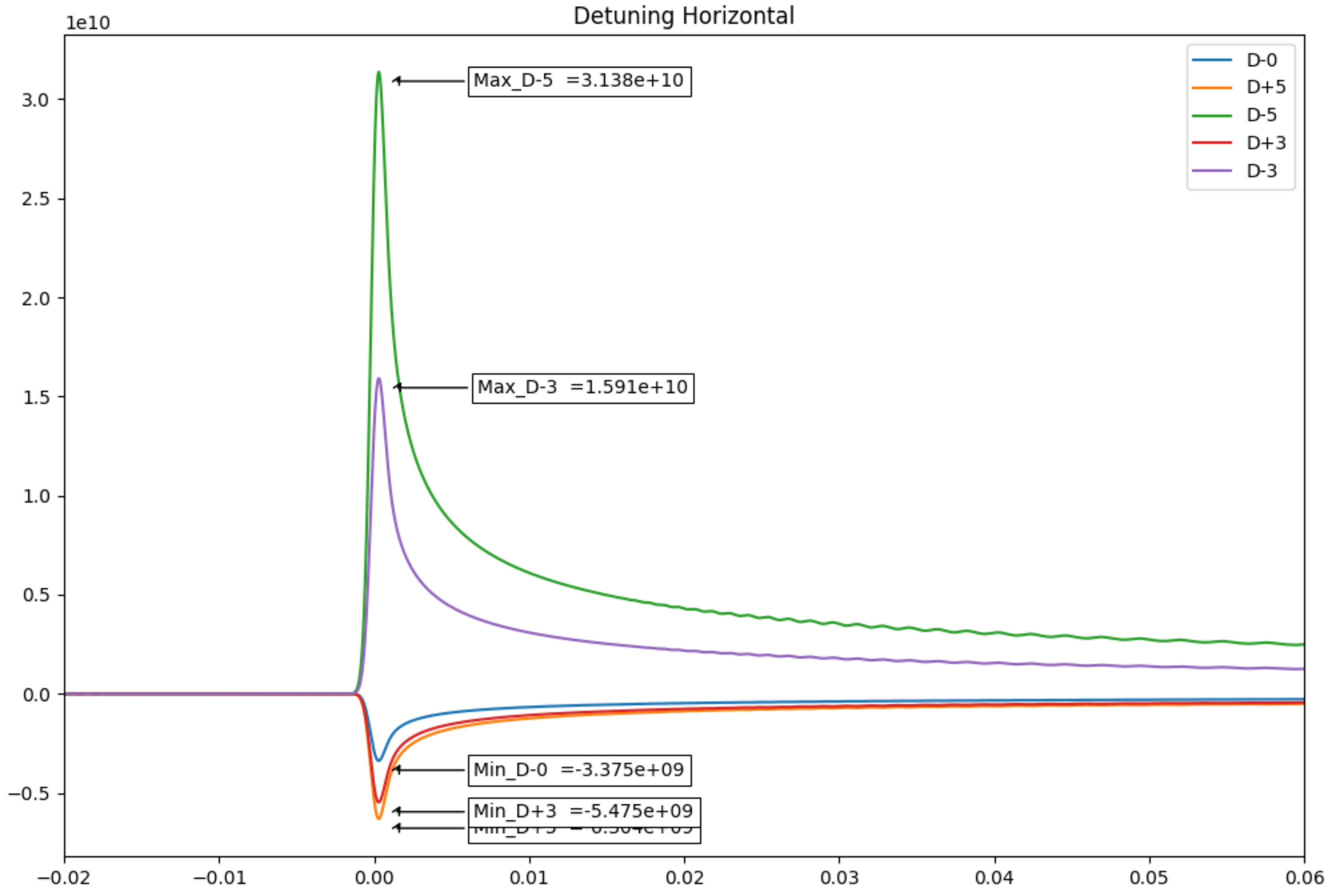
FCC main Ring

Minimizing Detuning impedance



FCC main Ring

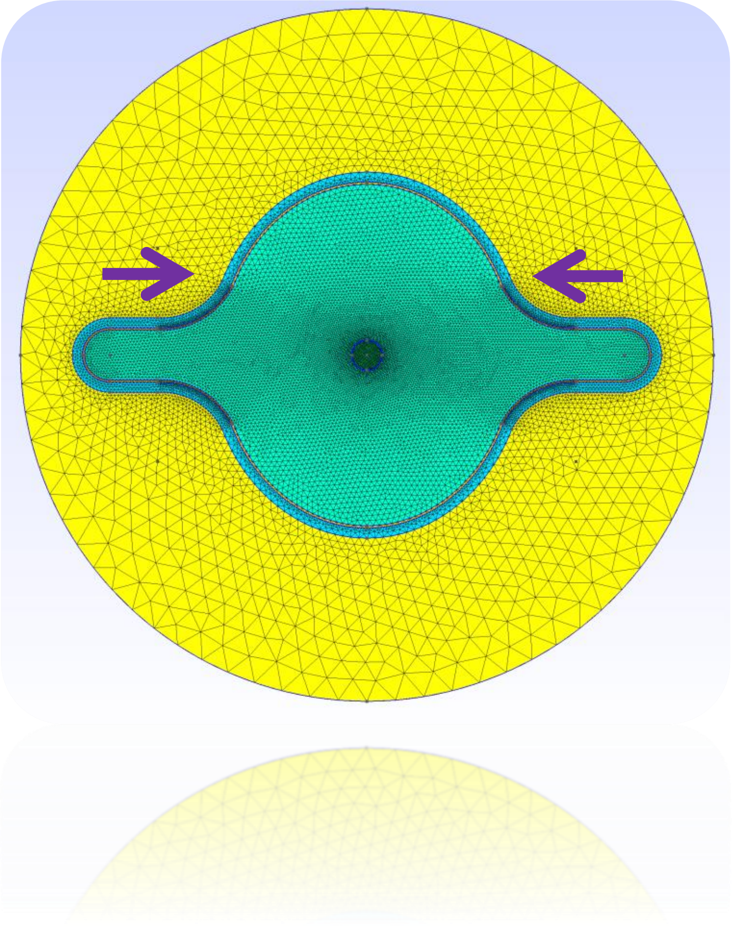
Minimizing Detuning impedance

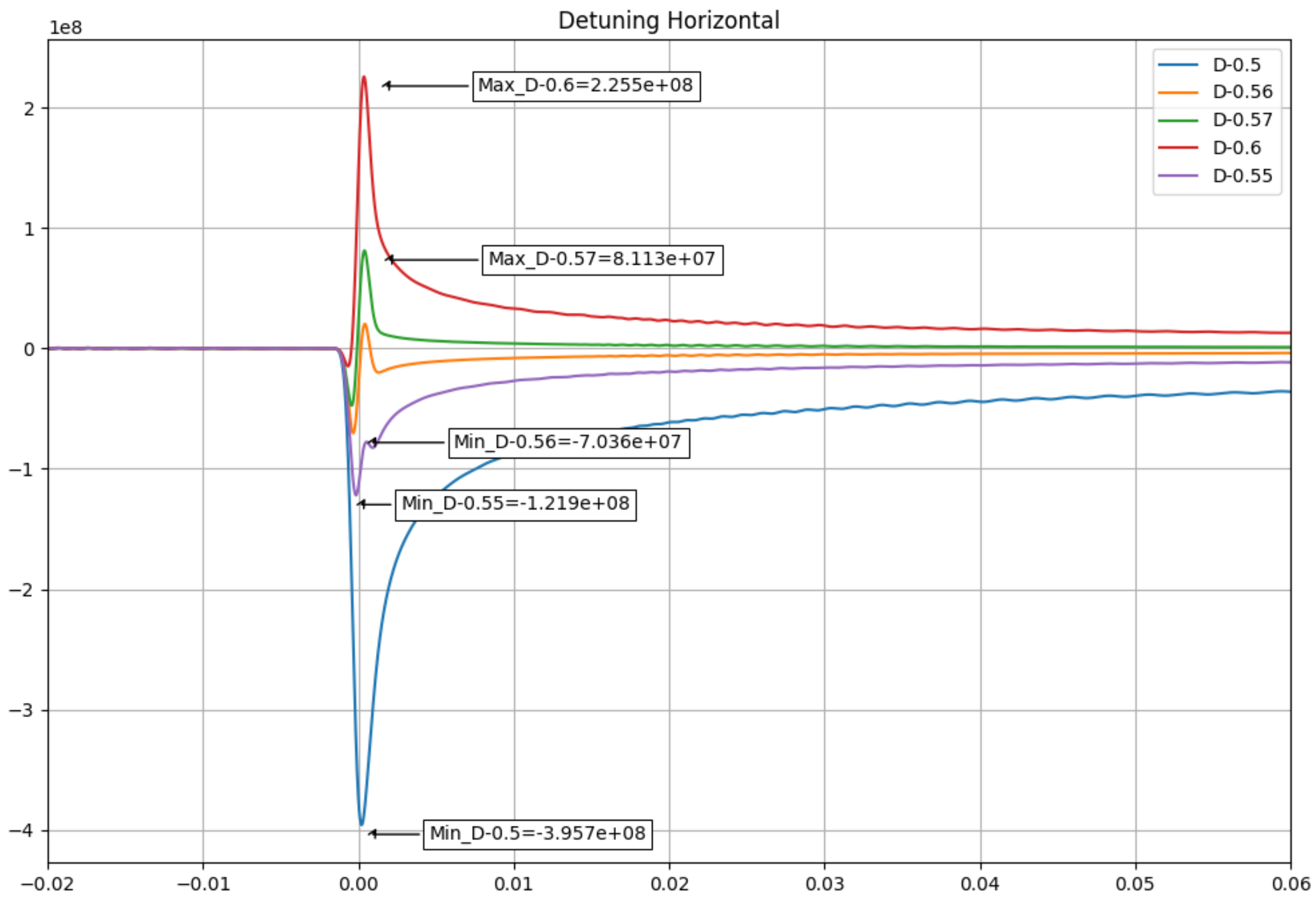


FCC main Ring

Minimizing Detuning impedance

Best ~ 560 – 570 μm (each side)

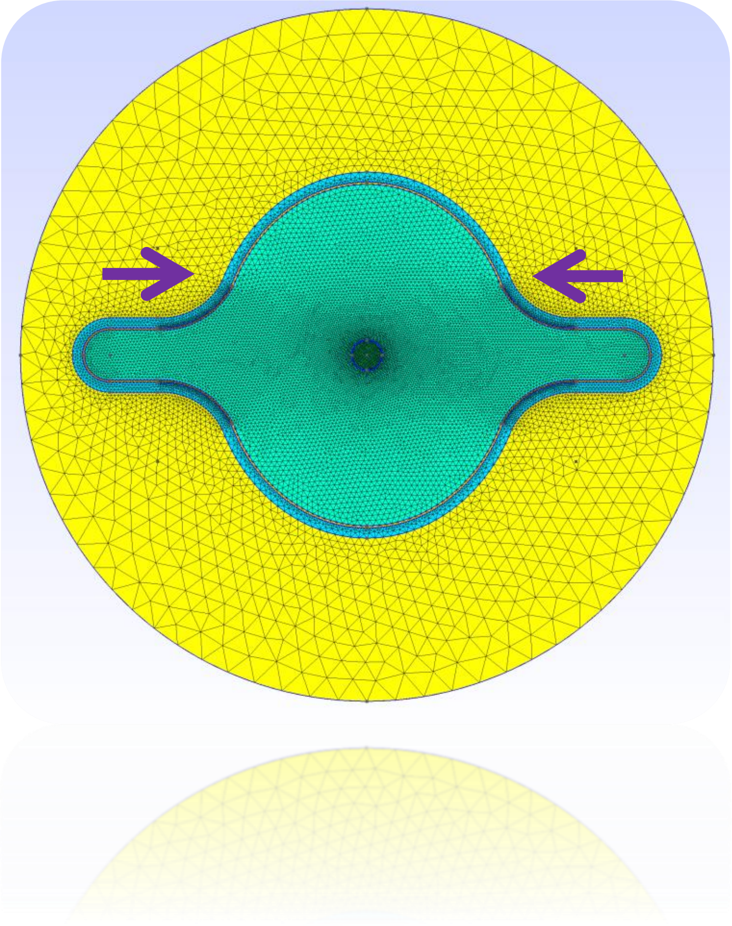


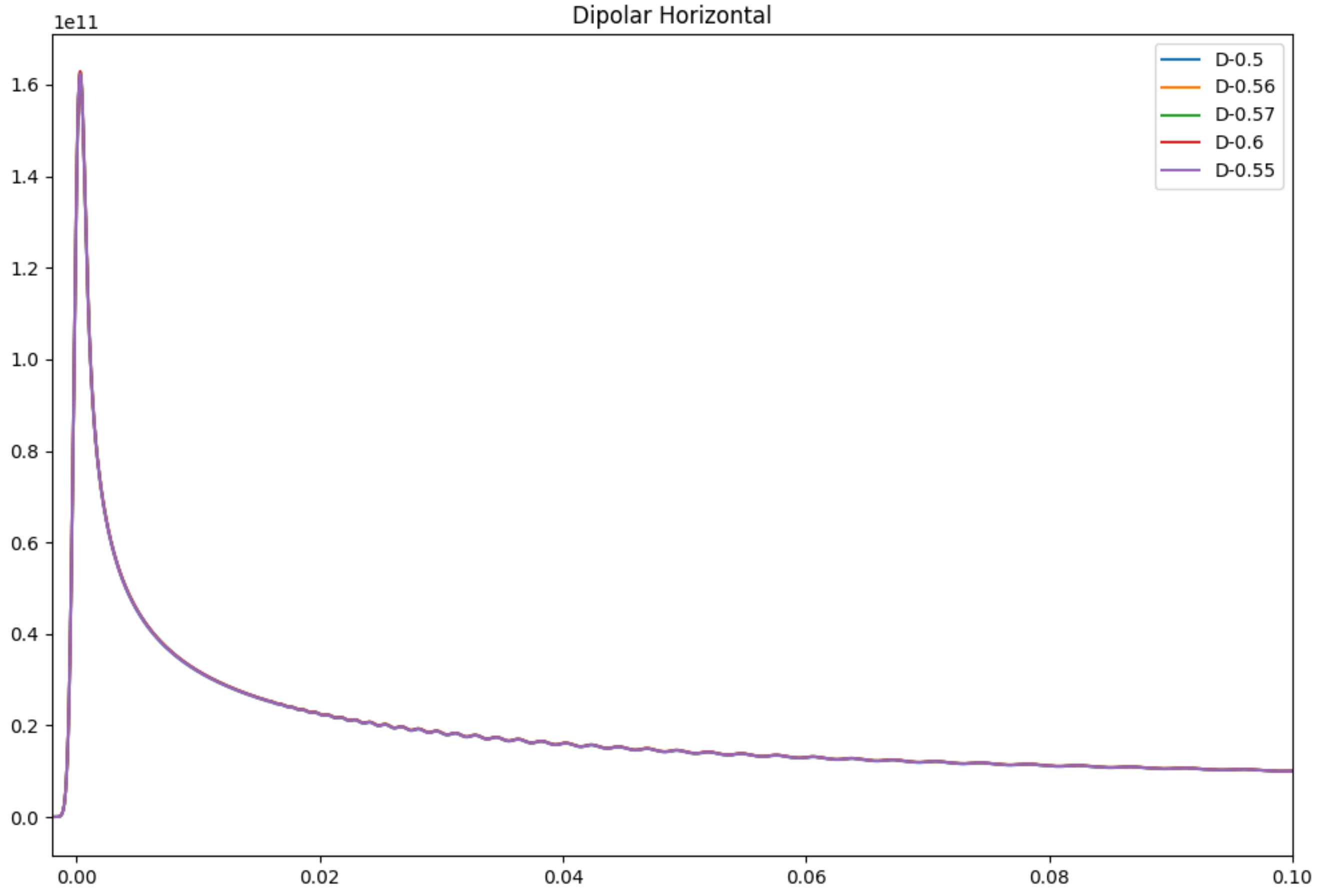


FCC main Ring

Minimizing Detuning impedance

Best ~ 560 – 570 μm (each side)





FCC Booster Ring

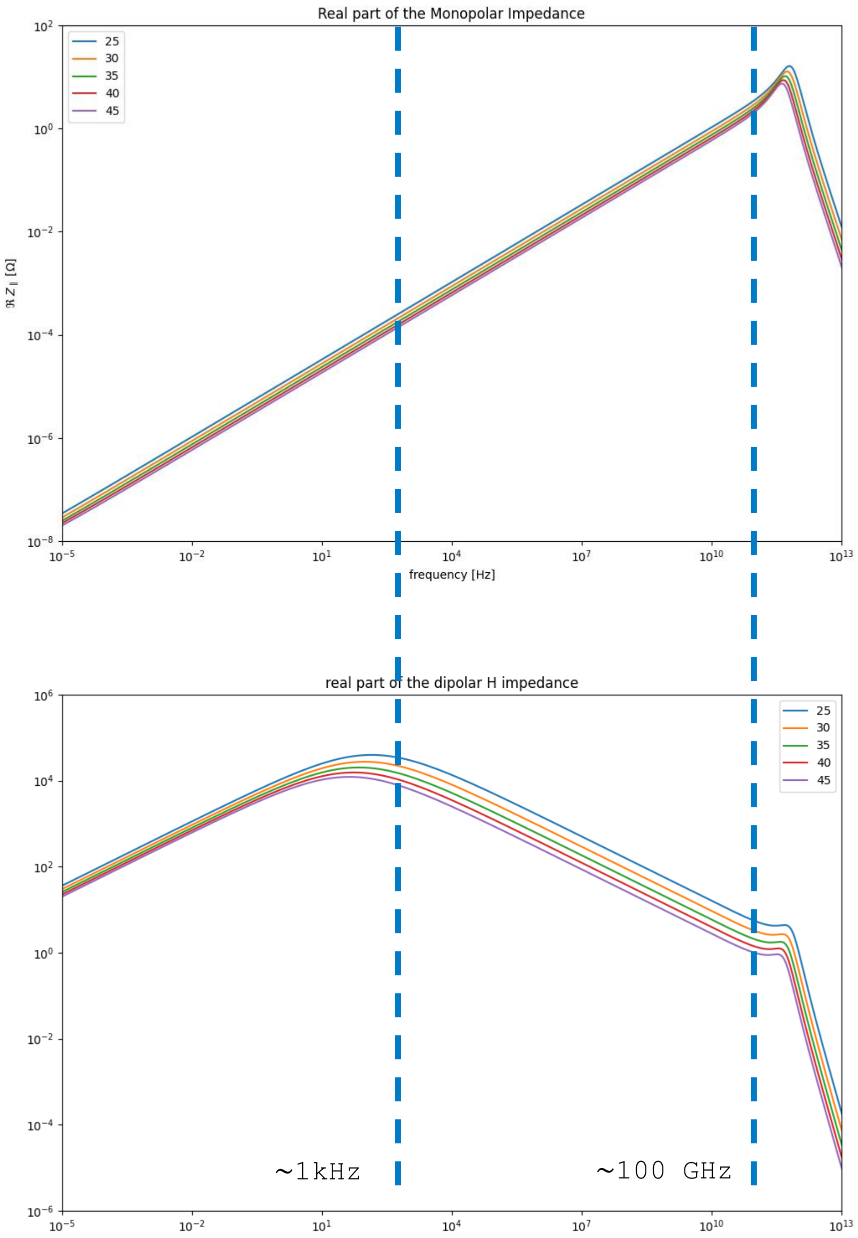
Different Senarios

FCC Booster Ring

Impedance, Stainless Steel, different radius

$$Z_{\parallel}(\omega) \equiv Z_0^{\parallel}(\omega) \approx (1 - i\,\mathrm{sgn}(\omega))\frac{L}{2bc}\sqrt{\left(\frac{Z_0 c}{4\pi}\right)\frac{2|\omega|}{\pi\sigma}},$$

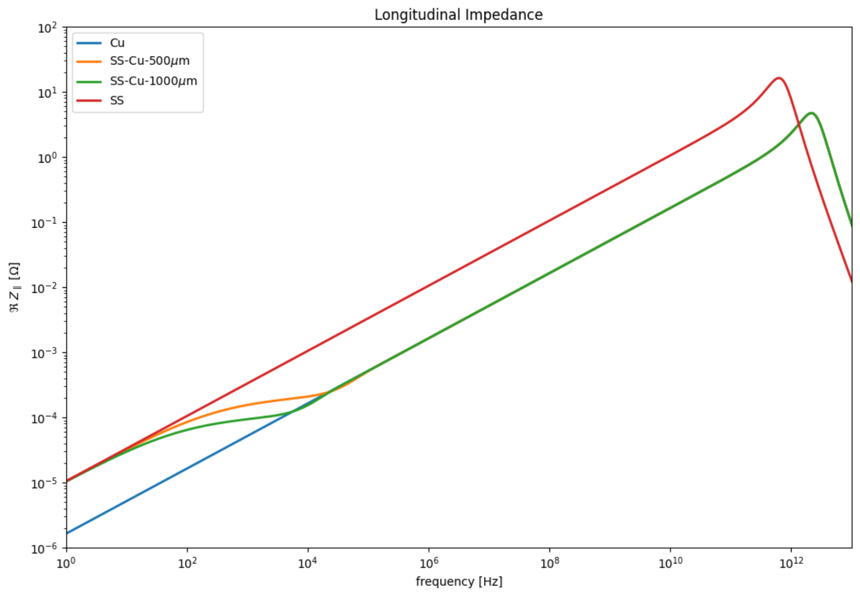
$$Z_{\perp}(\omega) \equiv Z_1^{\perp}(\omega) \approx (1 - i\,\mathrm{sgn}(\omega))\frac{c}{\omega}\frac{L}{b^3 c}\sqrt{\left(\frac{Z_0 c}{4\pi}\right)\frac{2|\omega|}{\pi\sigma}}.$$

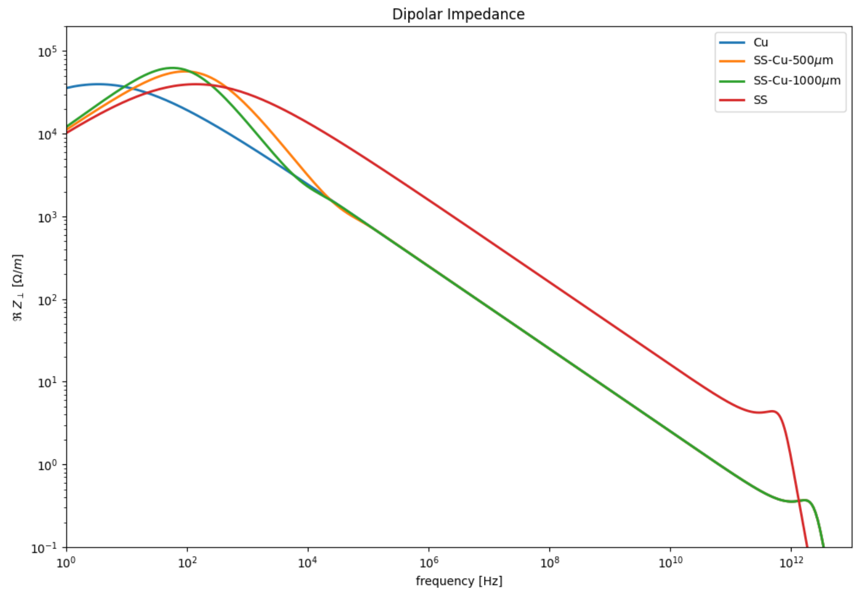


Booster Ring

Different senarios

1. Stainless Steel
2. Stainless Steel +   500 μm Copper
3. Stainless Steel + 1000 μm Copper
4. Copper



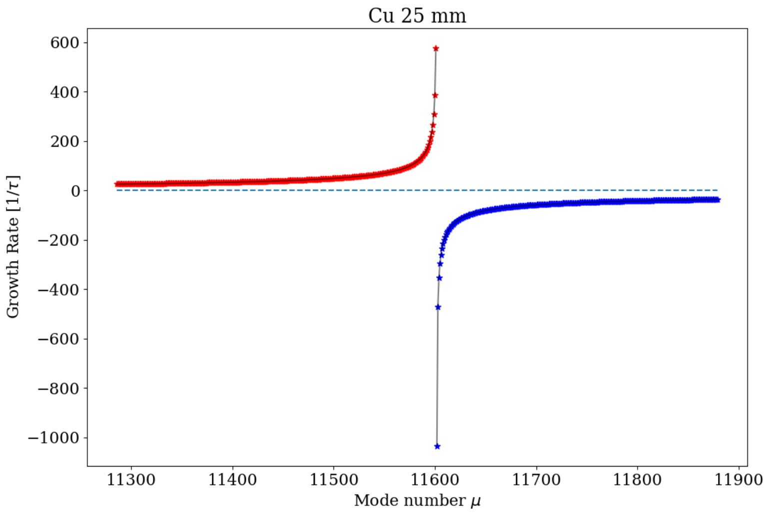


Booster Ring

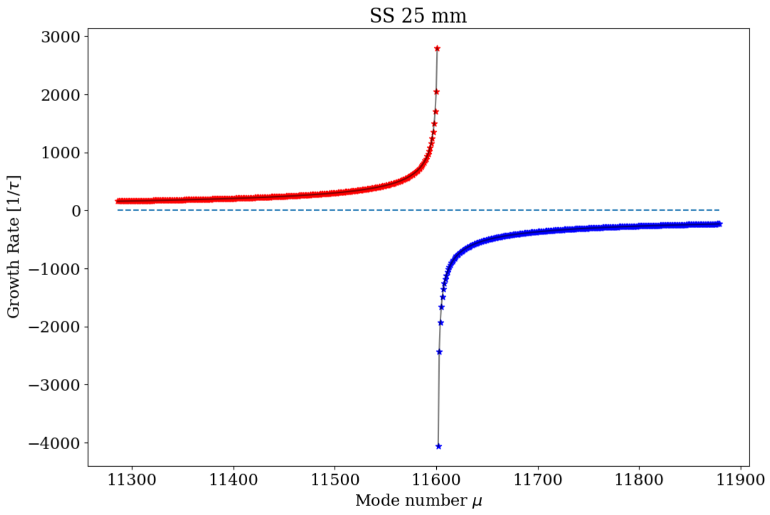
Different senarios, CBI

Parameters	Value
Intensity	2.14e11
N Bunch	11200
σ_z	5.6 mm
α	28.6 e-6
Q_x	222.2

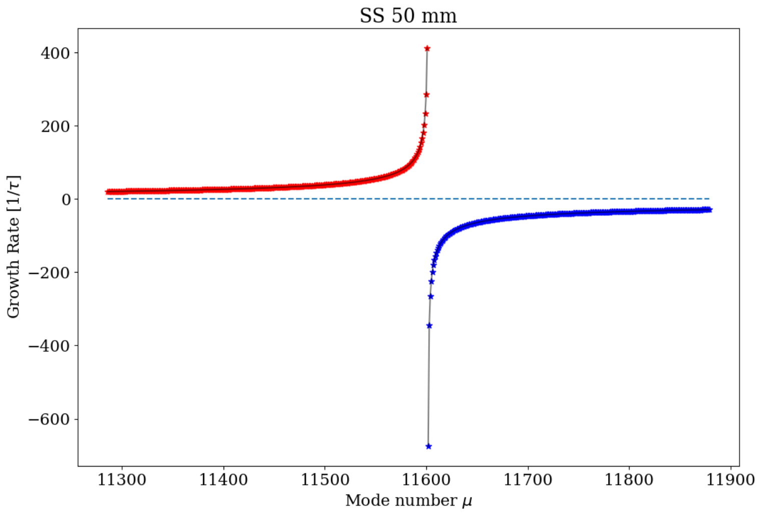
Copper R = 25 mm



Stainless Steel R = 25 mm



Stainless Steel R = 50 mm



Outlooks and Conclusion

A conclusion is the place where you got tired thinking. Martin H. Fischer

- VACI suite is a versatile tool for calculating resistive wall impedance in arbitrary beam pipe cross sections.
- Benchmarked against IW2D, analytical formulas, and Yokoya's code:
  - ➢ Demonstrated accuracy and reliability.
- Calculation of resistive wall impedance for the FCC main ring.
  - ➢ Omitted detuning impedance.
- Capabilities of VACI suite include:
  1. Impedance calculation
  2. Wakefield analysis
  3. Wake potential computation
  4. Kick and loss factor calculation
  5. Coupled-bunch instability (CBI) analysis
- Results are easily integrated with XSuite.
- VACI suite will be freely available after the publication of my paper. “https://github.com/alirajabi87/VACI”

Thank you

Contact

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