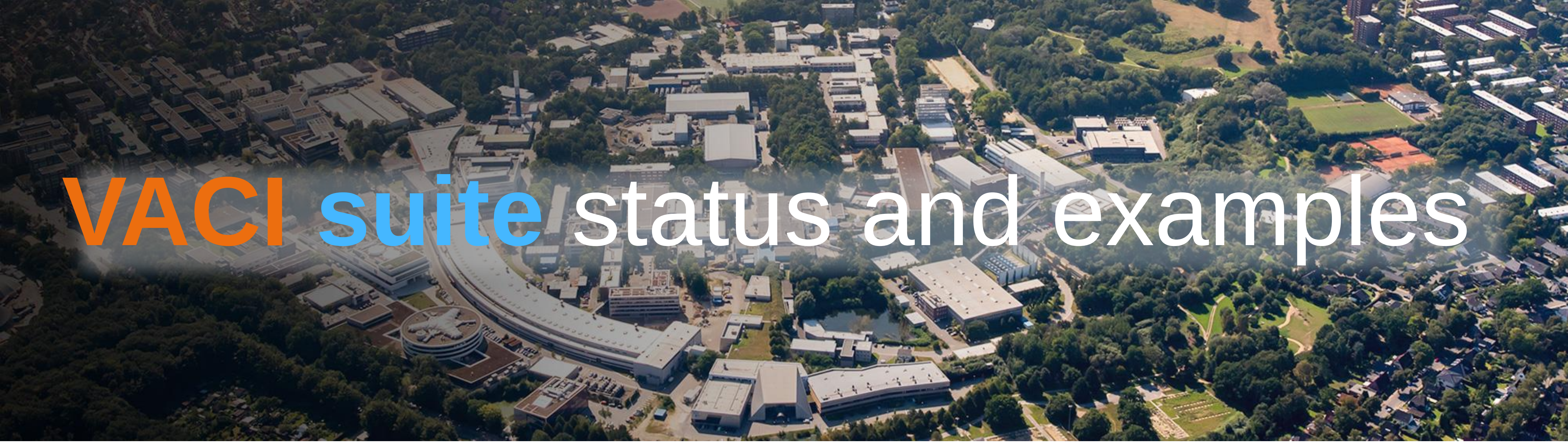


VACI suite status and examples

Ali Rajabi

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

FUTURE CIRCULAR COLLIDER

DESY.

HELMHOLTZ

Contents

Introduction

VACI

Simulation Codes

Electromagnetic Solvers

Free	**Commercially available**
• ImpedanceWake2D by Mounet	• CST Microwave Studio
• BeamImpedance2D by Niedermayer **	• GDFIDL
• Yokoya's Code ***	
• VACI Suite	

* https://twiki.cern.ch/twiki/bin/view/ABPComputing/ImpedanceWake2D

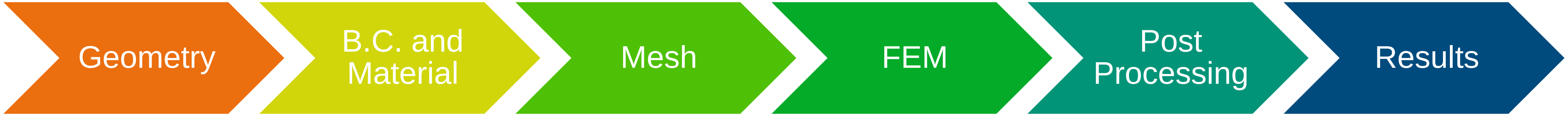
** Niedermayer, Uwe, Oliver Boine-Frankenheim, and Herbert De Gersem. "Space charge and resistive wall impedance computation in the frequency domain using the finite element method." *Physical Review Special Topics-Accelerators and Beams* 18.3 (2015): 032001.

*** Yokoya, Kaoru. "Resistive wall impedance of beam pipes of general cross section." Part. Accel. 41.KEK-Preprint-92-196 (1993): 221-248.

VACI suite a versatile tool to calculate RW impedance and Wakefield

Introduction

VACI (VAcuum Chamber Impedance) suite



Resistive Wall impedance

Maxwell's Equations

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

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

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

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.

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

Resistive Wall impedance

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

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

Single particle

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

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

$$\vec{J}_s(\vec{r}_\perp,z,t) = q_1\sigma(\vec{r}_\perp)\delta(z-vt)\vec{v}$$

$$\vec{\underline{J}}_s(\vec{r}_\perp,z,\omega) = q_1\sigma(\vec{r}_\perp)e^{-i\omega z/v}\vec{e}_z.$$

Integrating over the beam in FD
Like Convolution in TD

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

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

Resistive Wall 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 $m, n = 0, \pm1, \pm2, \ldots$

Considering $m \geq 0$ instead of $m = 0, \pm1, \pm2, \ldots$:

$$\bar{J}_m = J_m + J_{-m}$$
$$\bar{E}_m = E_m + E_{-m}$$

$$\Rightarrow \quad \bar{Z}_m(\omega) = -\frac{1}{Q^2} \int dV \left(E_m + E_{-m}\right)\left(J_m^* + J_{-m}^*\right)$$

For $m = 0$: $\quad \bar{Z}_0 = Z_{0,0}$

For $m \geq 1$: $\quad \bar{Z}_m = Z_{m,m} + Z_{m,-m} + Z_{-m,m} + Z_{-m,-m}$

Resistive Wall impedance

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

Applying Panofksy-Wenzel theorem:

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

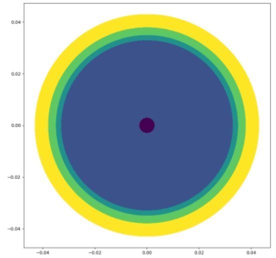
$$\begin{cases} k\,Z_x = \left(Z_{0,1} + Z_{0,-1}\right) + x_1 \bar{Z}_x + j\,y_1\left(-Z_{1,-1} - Z_{1,1} + Z_{-1,-1} + Z_{-1,1}\right) \\ \quad + 2\left(Z_{0,2} + Z_{0,-2}\right) x_2 + 2\left(Z_{0,2} - Z_{0,-2}\right) j\,y_2 \\ k\,Z_y = j\left(Z_{0,1} - Z_{0,-1}\right) + y_1 \bar{Z}_y + j\,x_1\left(-Z_{1,-1}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

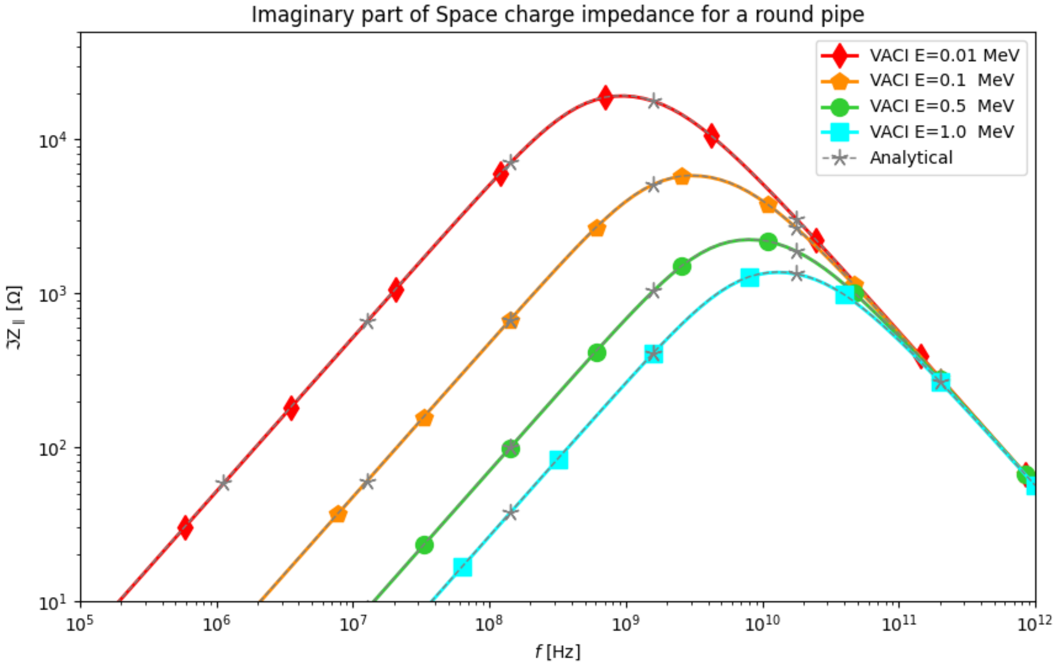
$$Z_x^{\text{driving}} = \bar{Z}_x / k \qquad Z_y^{\text{driving}} = \bar{Z}_y / k \qquad Z^{\text{detuning}} = -2\left(Z_{0,2} + Z_{0,-2}\right) / k$$

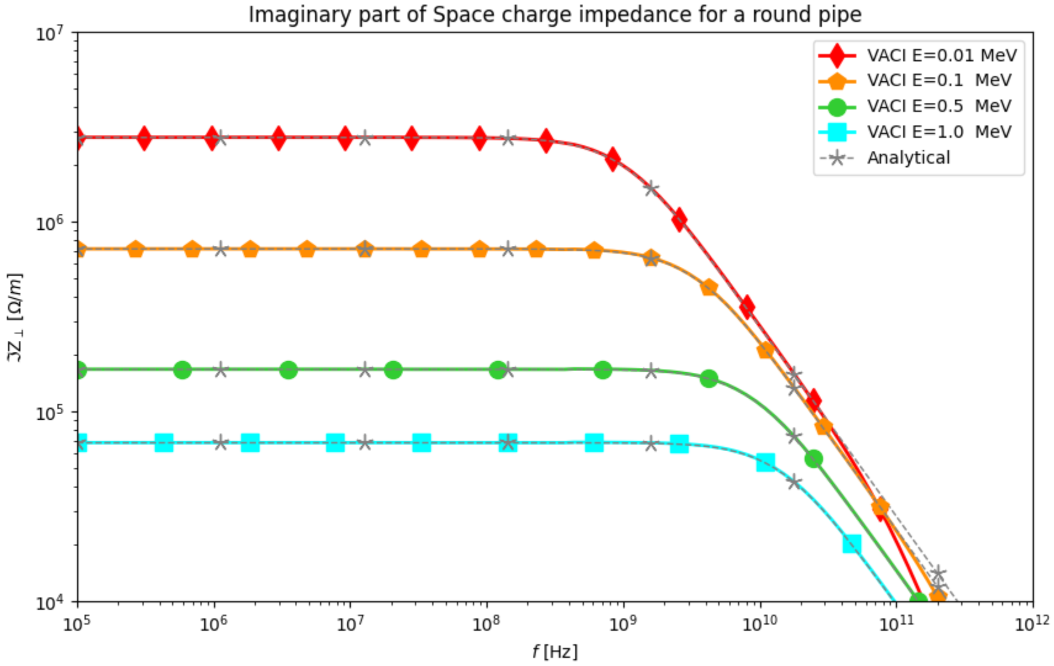
VACI Results

VACI results for Space-Charge

Round pipe



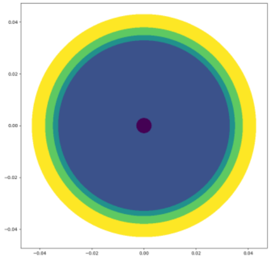




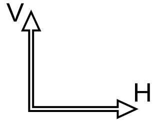
Gluckstern, Robert L. "Analytic methods for calculating coupling impedances." (2000).

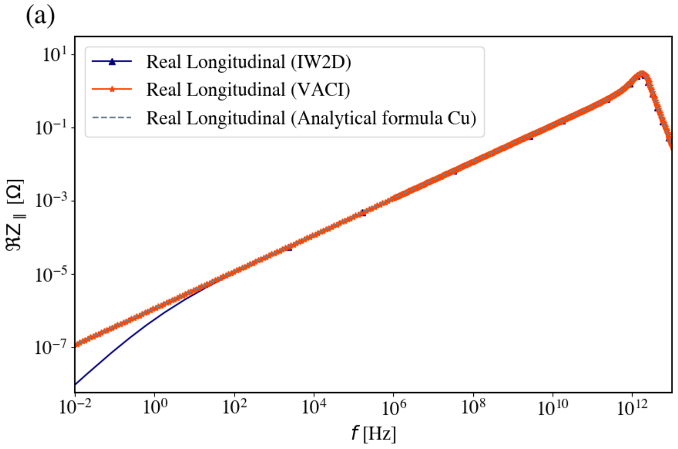
VACI results for Round pipe

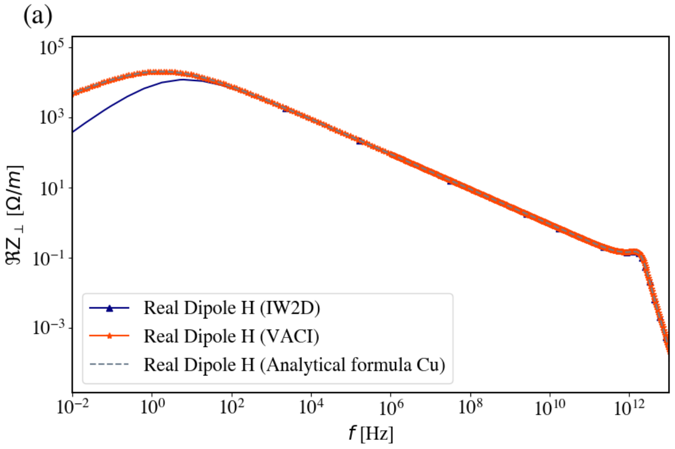
Impedance calculation

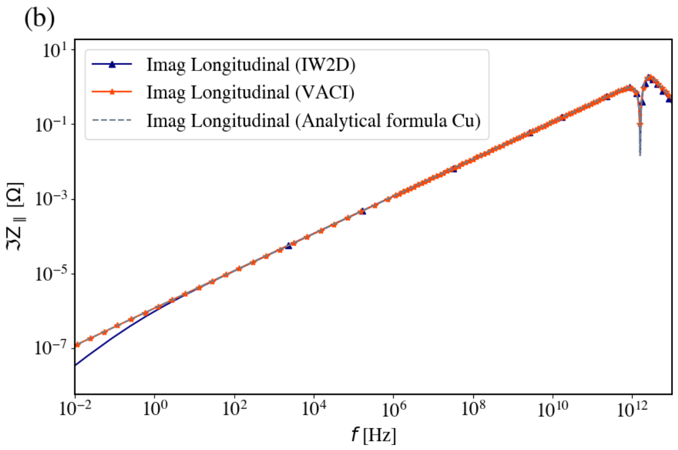


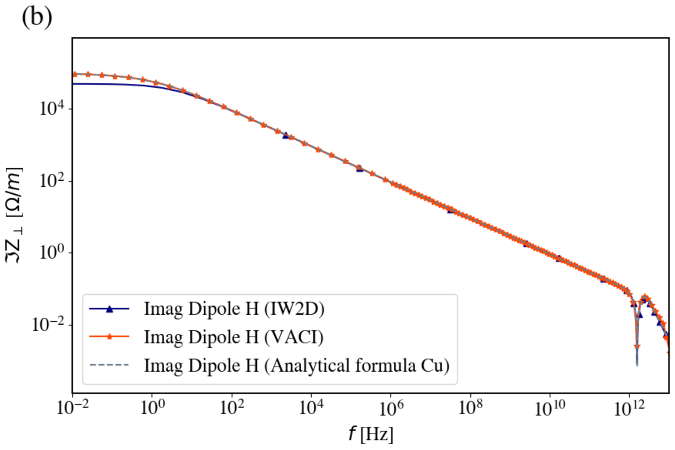
Energy: 15 GeV,
Round Pipe: r = 35 mm
Length = 1 m







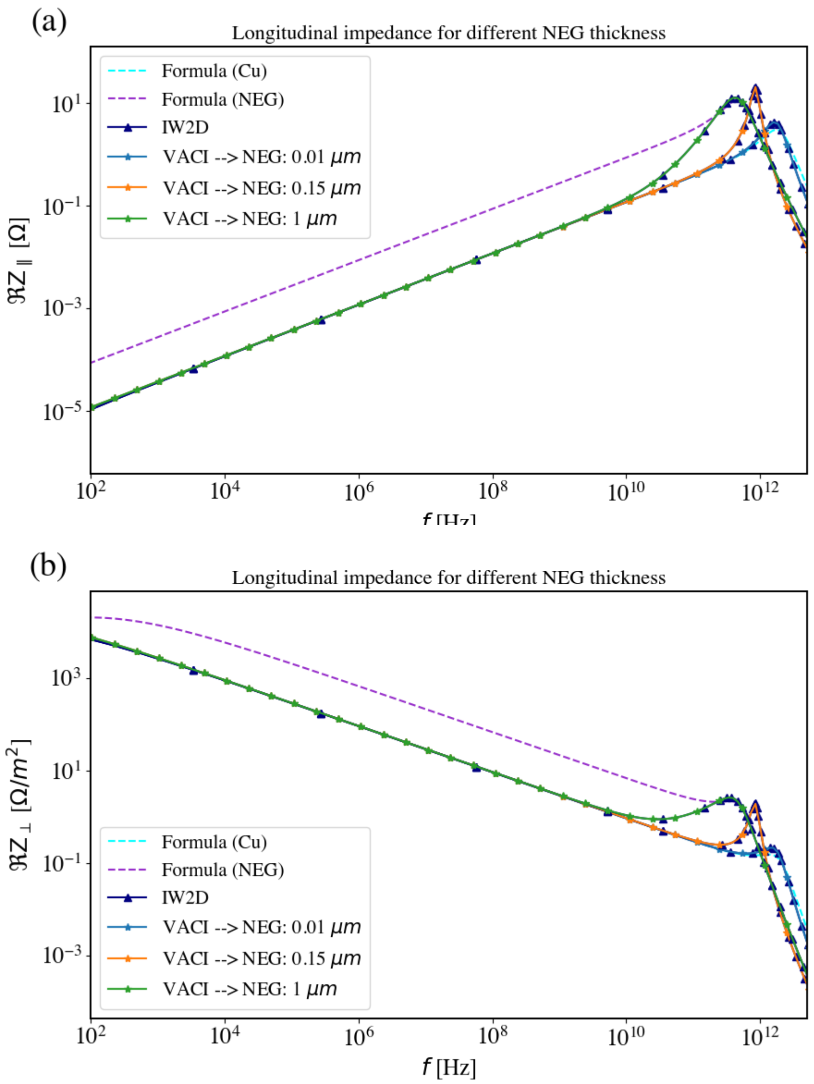


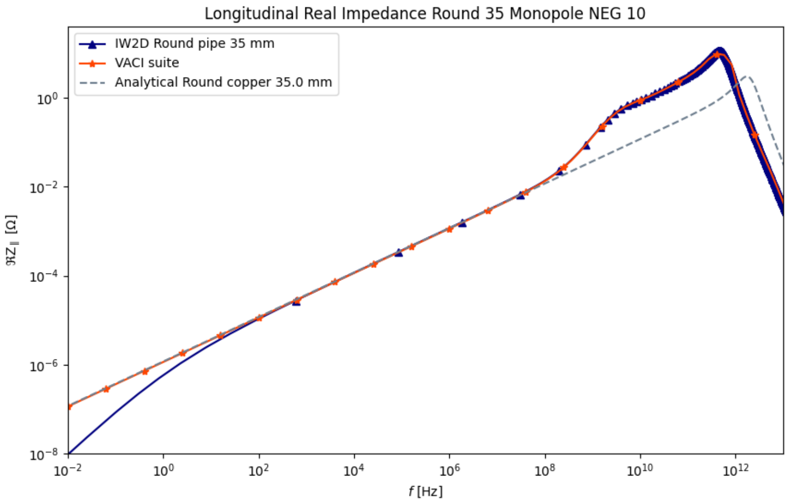


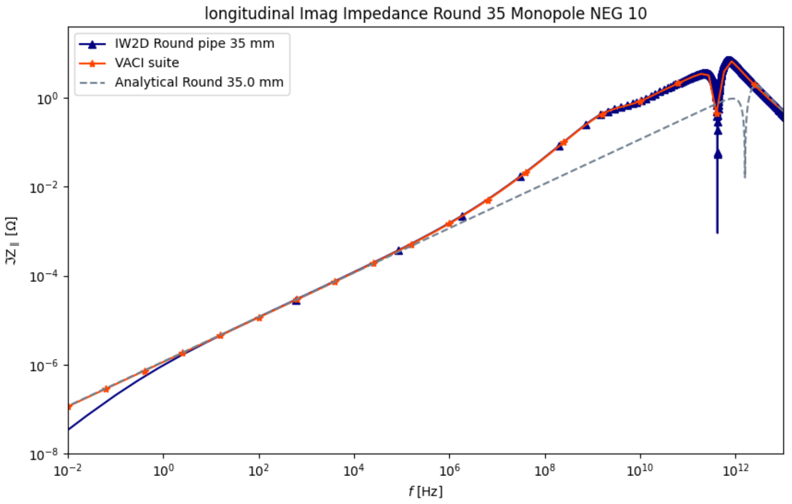
VACI results for Multi-Layer vacuum chamber

Impedance calculation of Round pipe With NEG coating

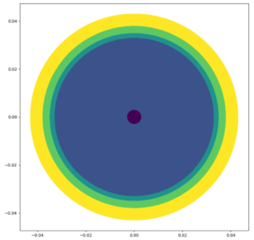
NEG properties:
$\sigma = 1.098e6$,
Thichness: 10 μm
Material: TiZrV alloy

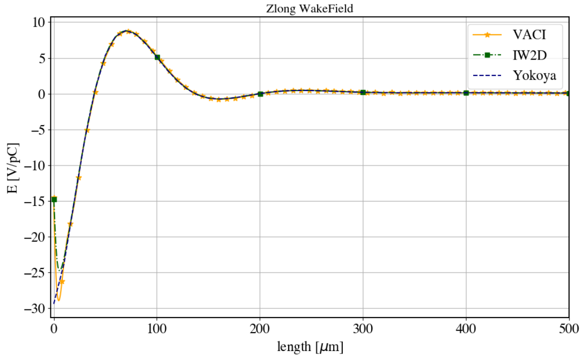


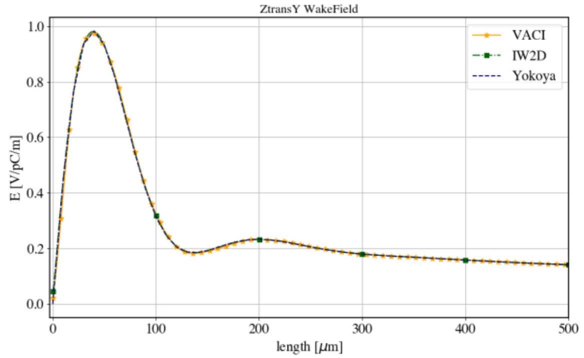


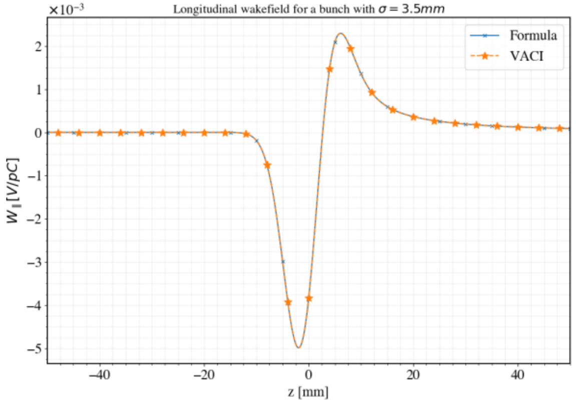


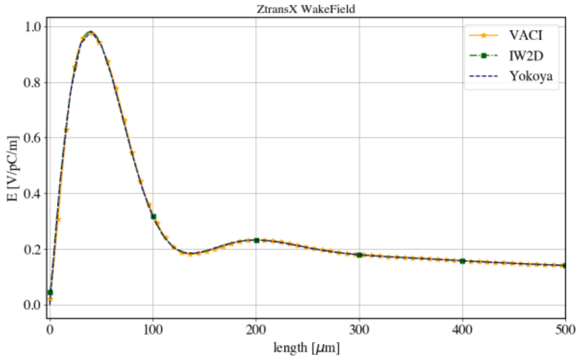
Wakefield and Wake-potential

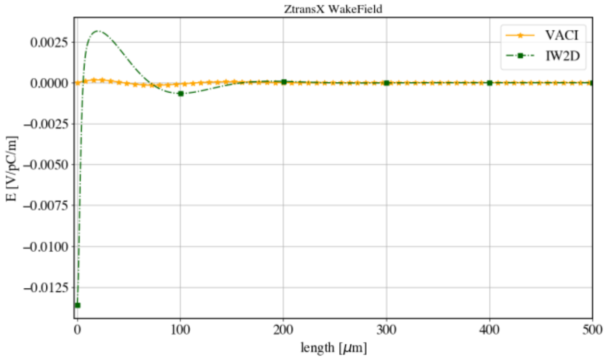


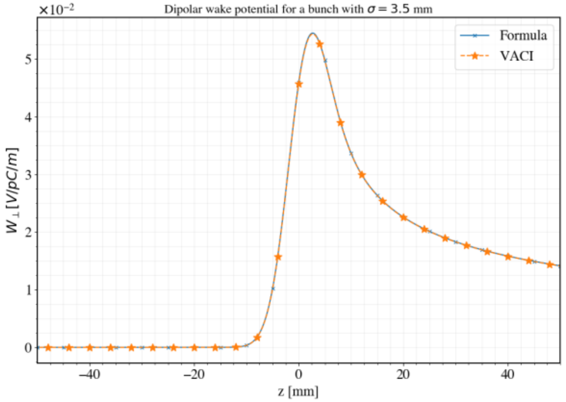










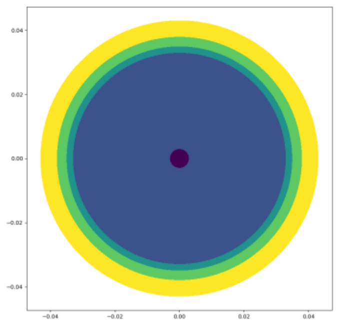


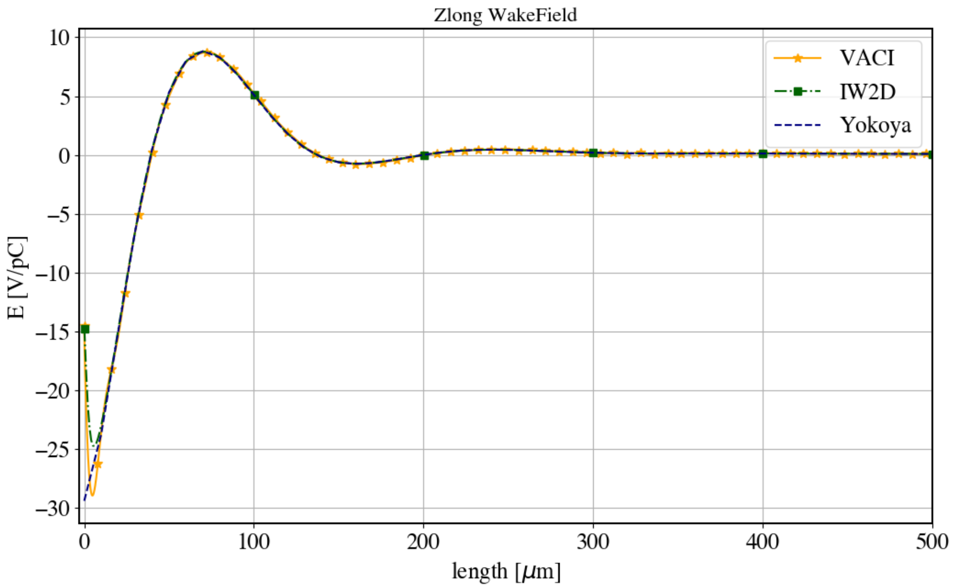
iFFT method:

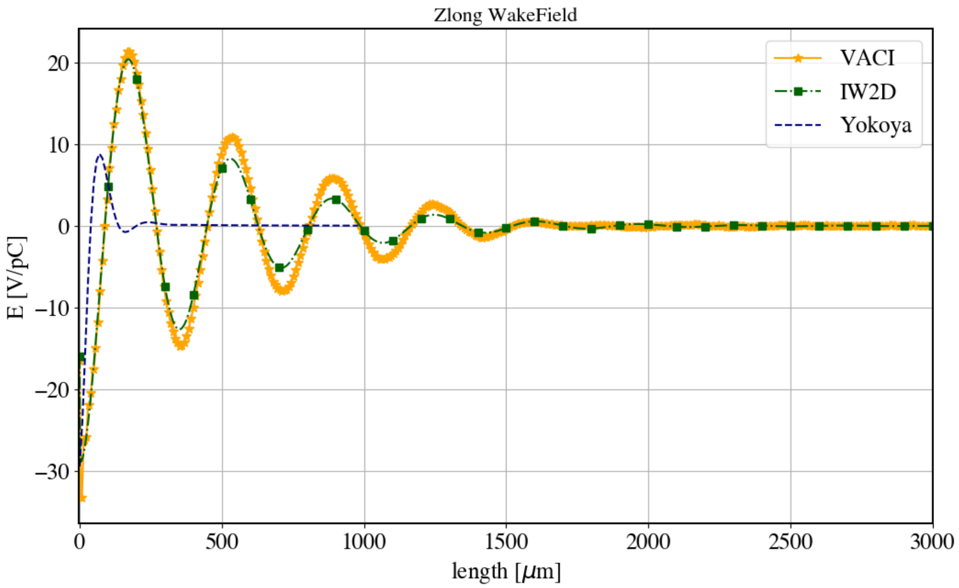
uneven sampling and a piecewise polynomial interpolation (cubic Hermite interpolation)

{Based on *Nicolas Mounet* Ph.D. thesis + some small upgrades}

Wakefield and Wake-potential (NEG)





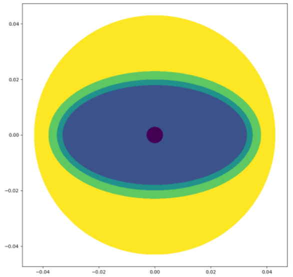


VACI results for Elliptical pipe

Impedance calculation

Energy: 15 GeV,
Ellipese pipe: r1 =35 mm- r2=20 mm,
Round Pipe: r = 20 mm
Yokoya's Form Factors:

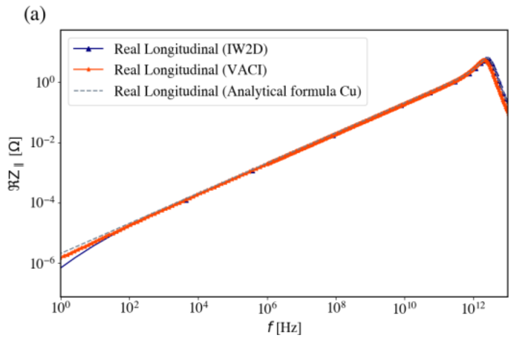
R [mm]	Long	X dip	Y dip	X quad	Y quad
20	1.0	0.46323	0.84038	-0.37701	0.38219

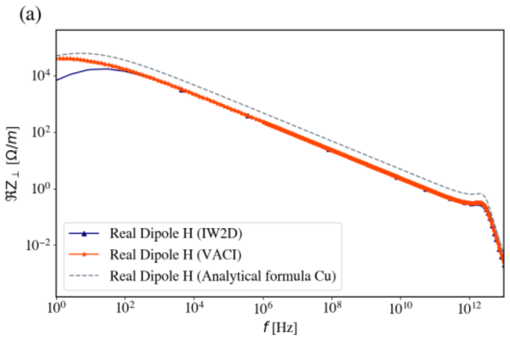


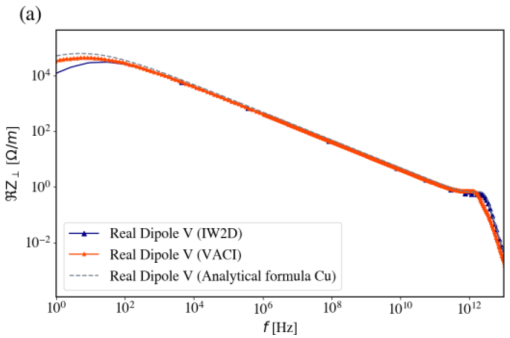
Monopole

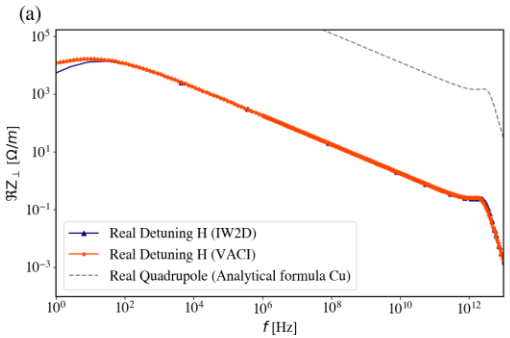
Dipole

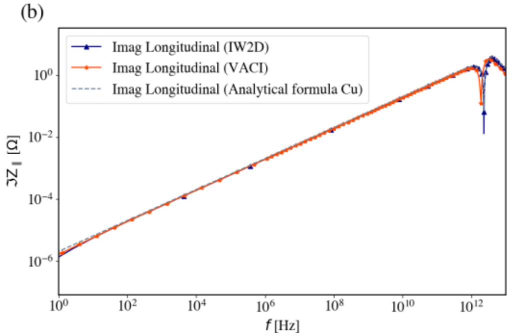
Detuning

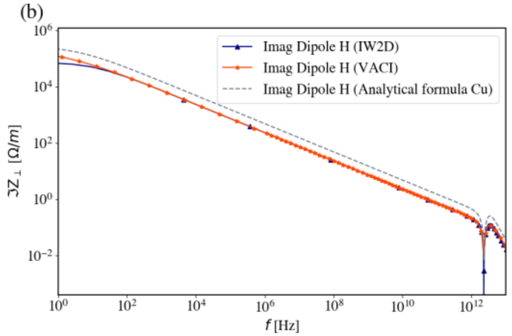


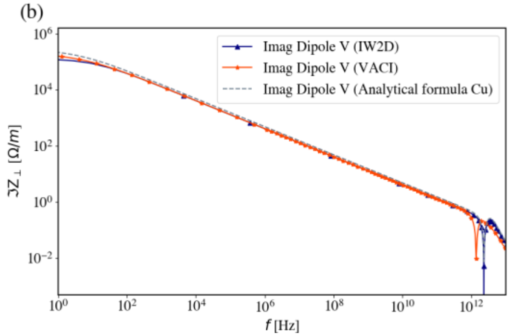


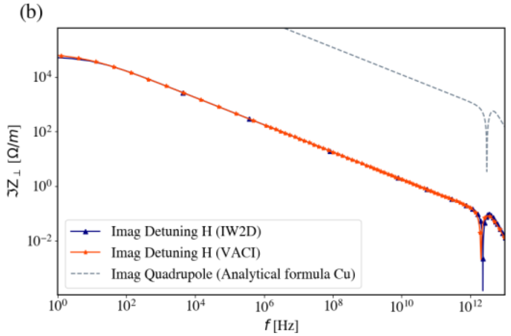




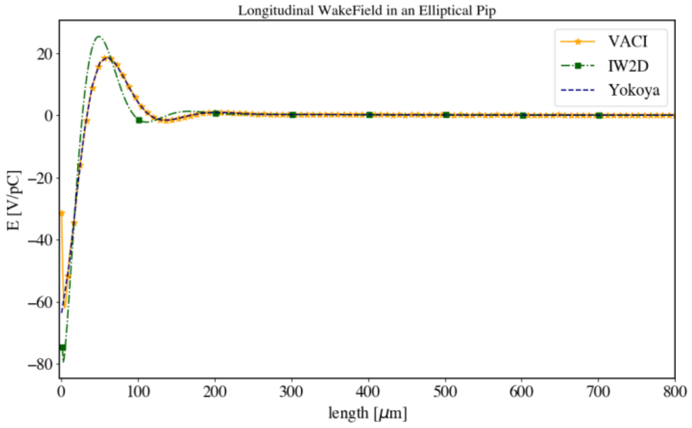


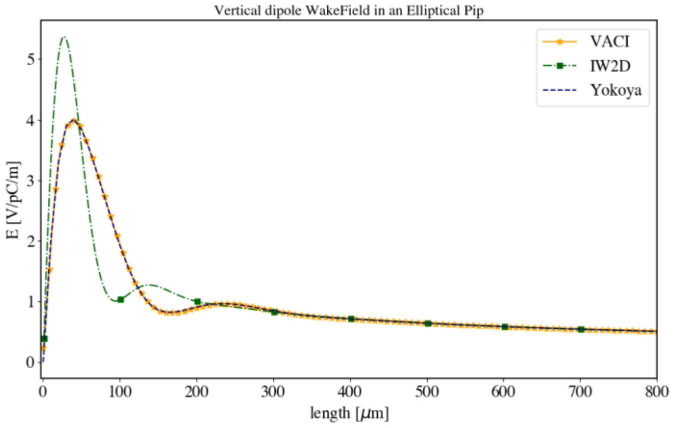


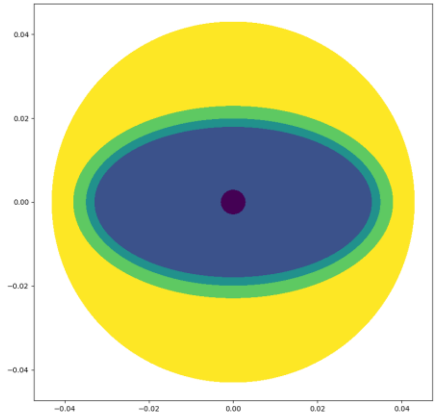


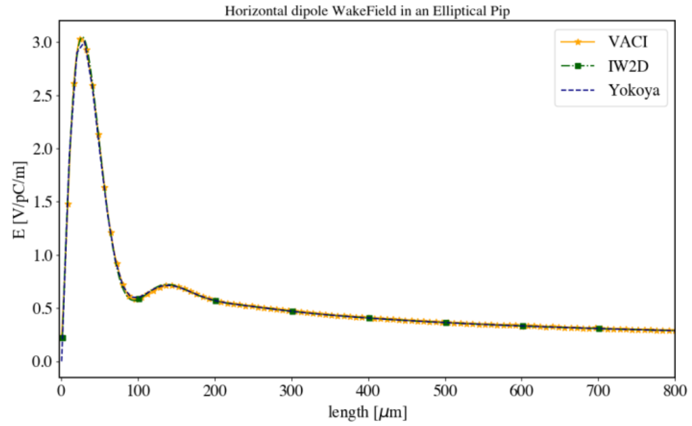


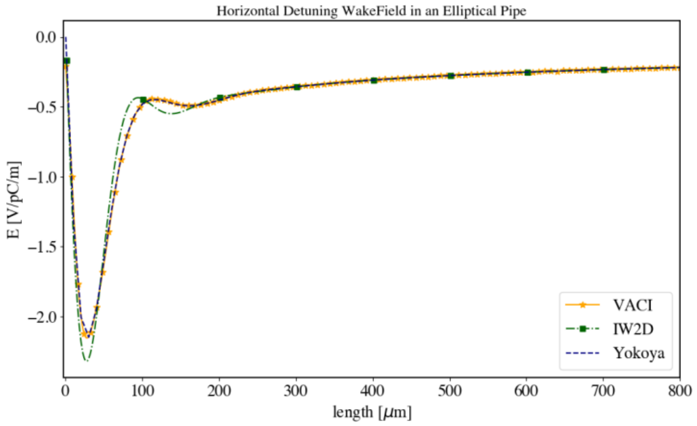
VACI also → Wakefields with and without NEG

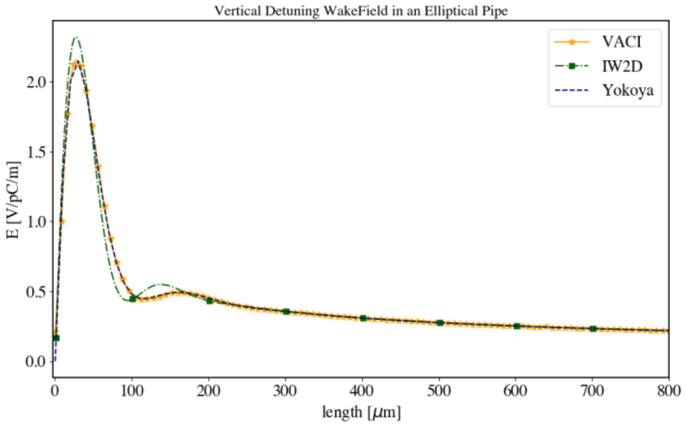












FCC Vacuum Chamber

FCC booster and main rings Geometries

Impedance sources

I. Resistive Wall Impedance

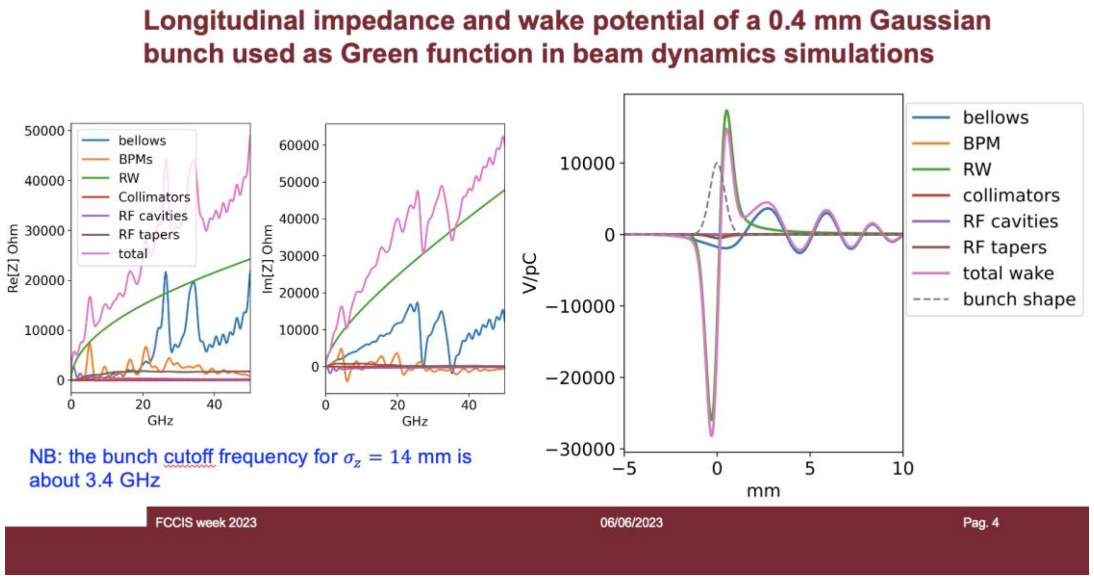
II. RF Cavities and RF Cavity Tapers

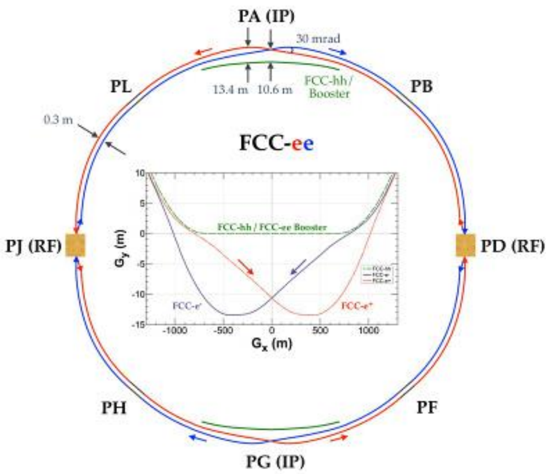
III. Synchrotron Radiation (SR) absorbers

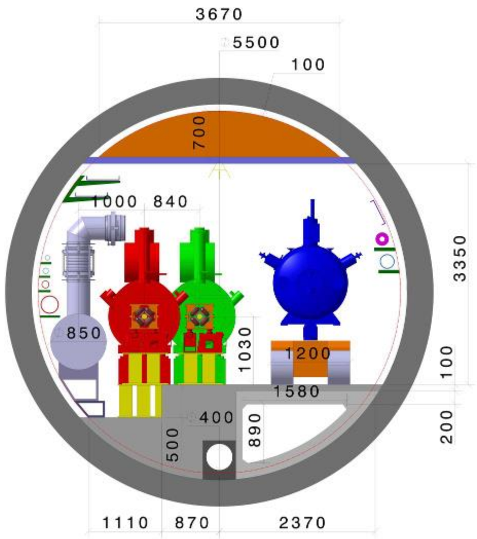
IV. Collimators

V. Beam Position Monitors

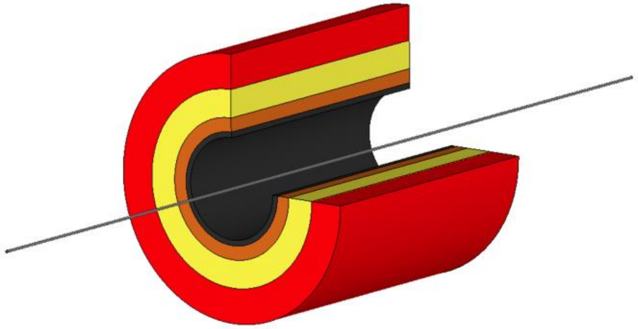
VI. Bellows



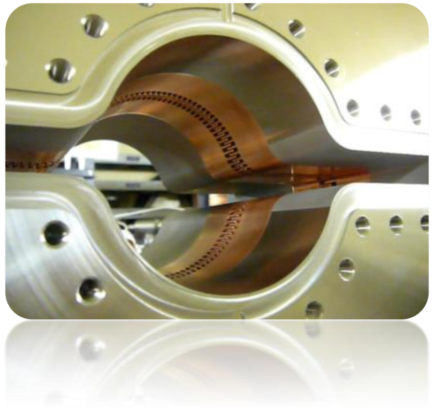




Booster ring



Main ring

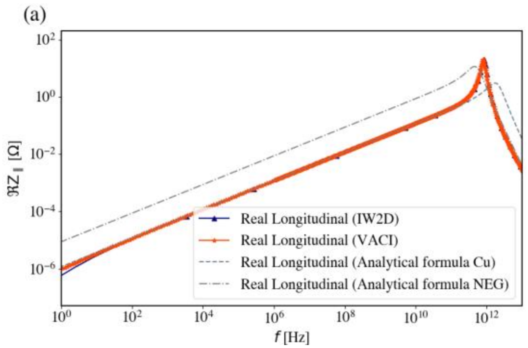


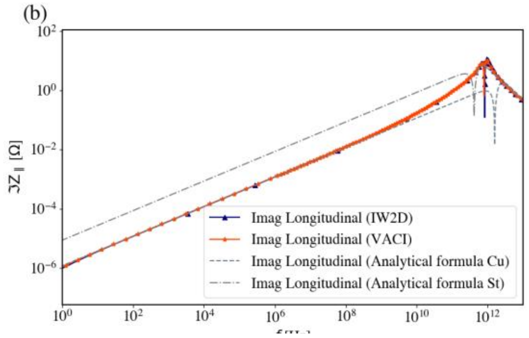
Courtesy to Mauro Migliorati

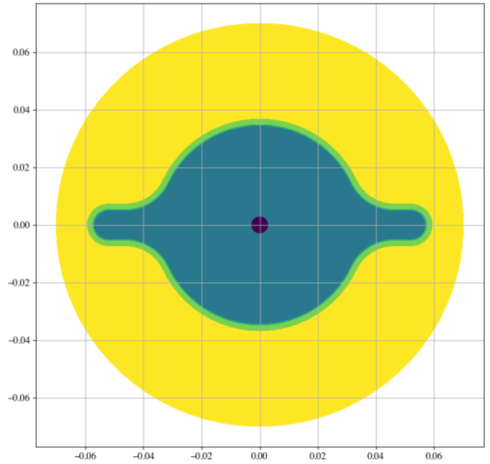
VACI results for FCC main ring

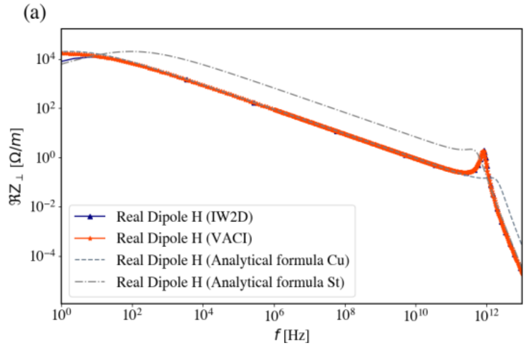
RW impedance

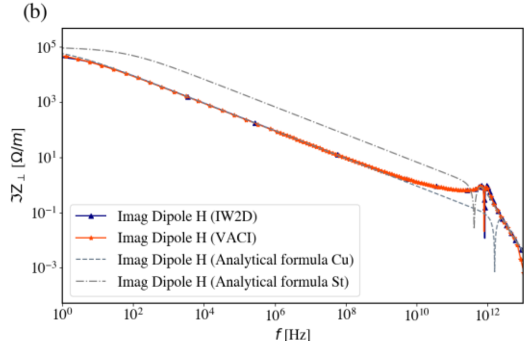
Copper Vacuum chamber
Length: 1m
NEG : 150 nm. $\sigma = 1.098e6$ s/m

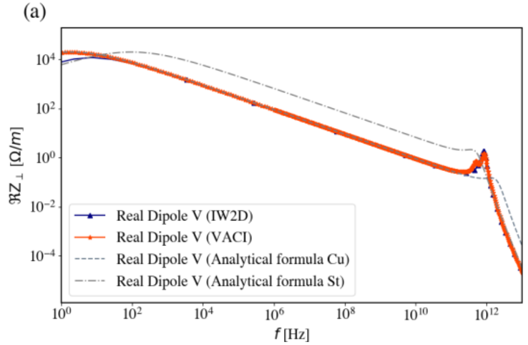


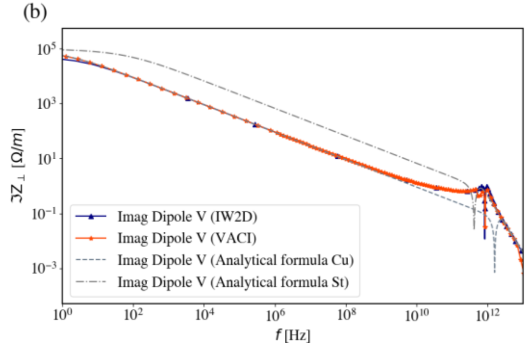


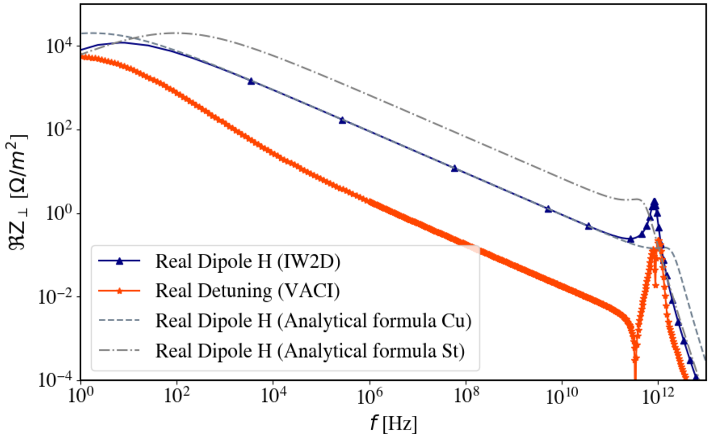








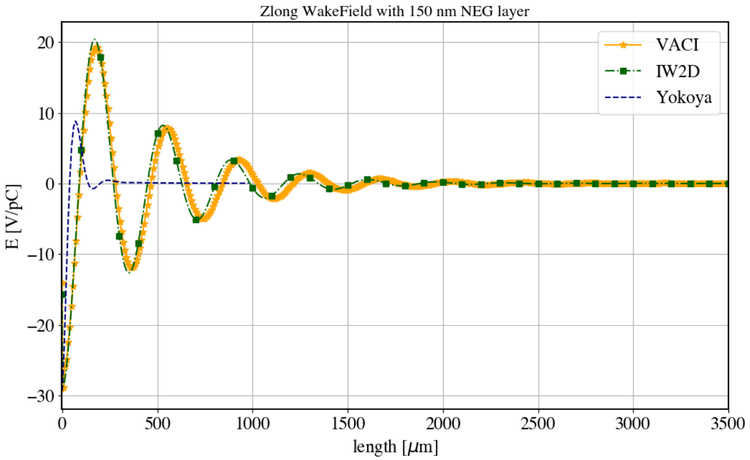


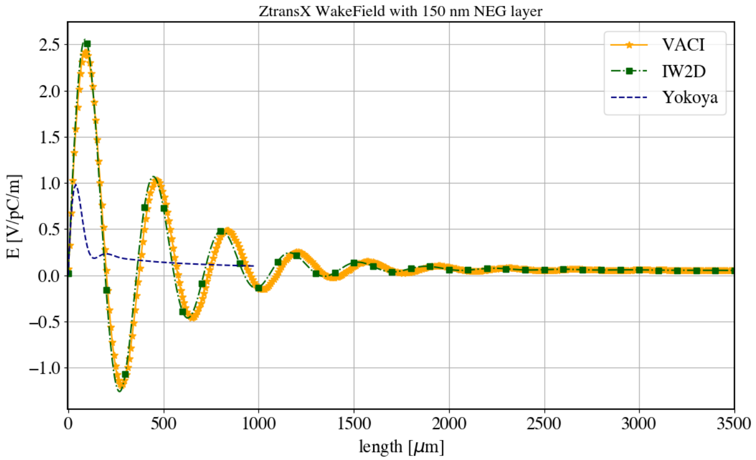


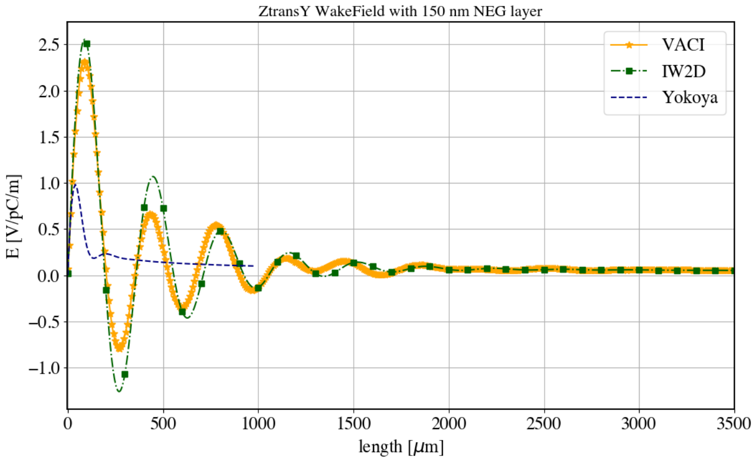
VACI results for FCC main ring

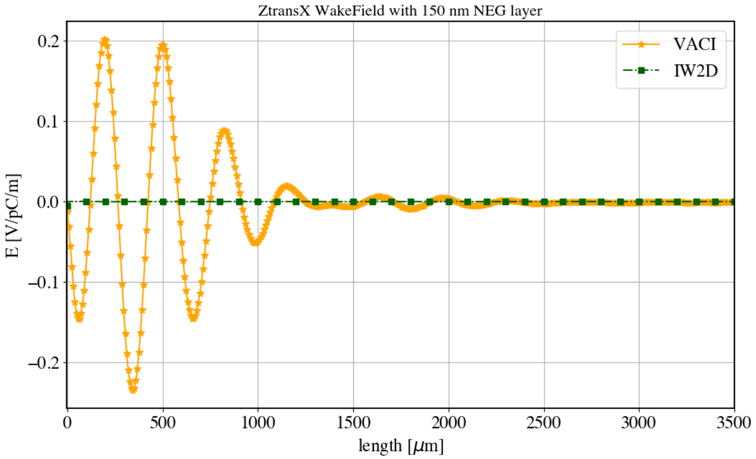
RW Wakefield

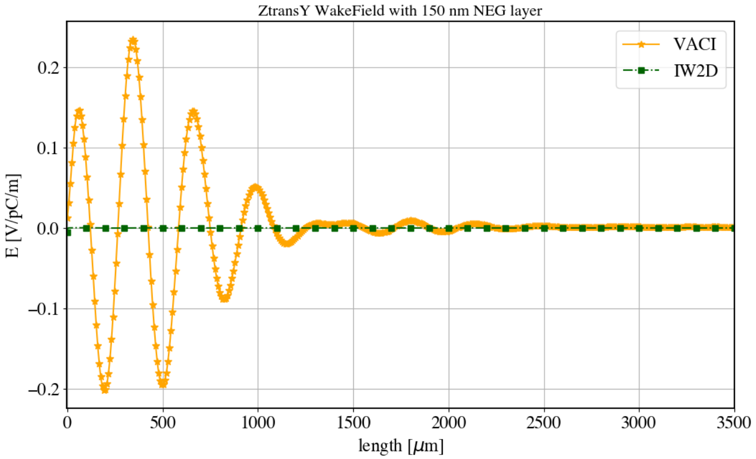
Copper Vacuum chamber
Length: 1m
NEG : 150 nm. $\sigma = 1.098e6$ s/m







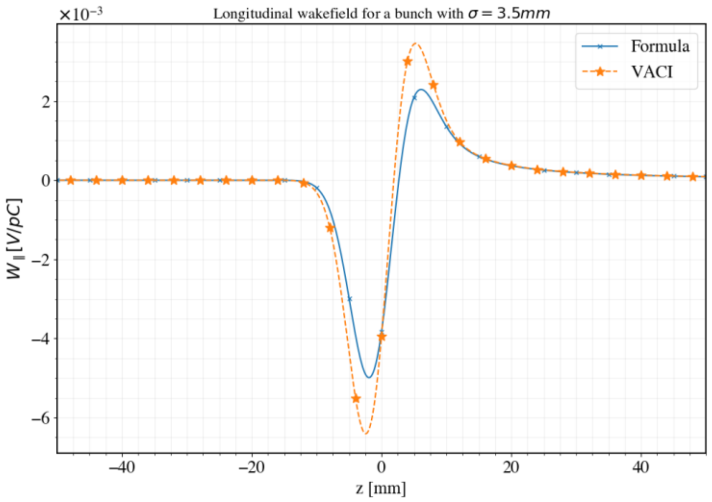


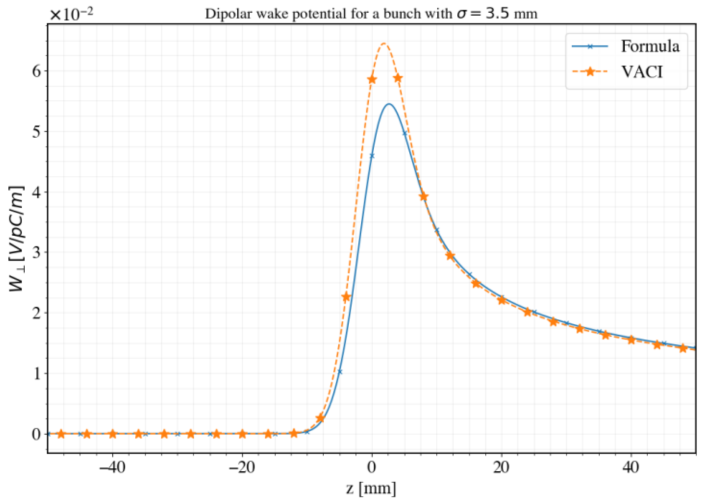


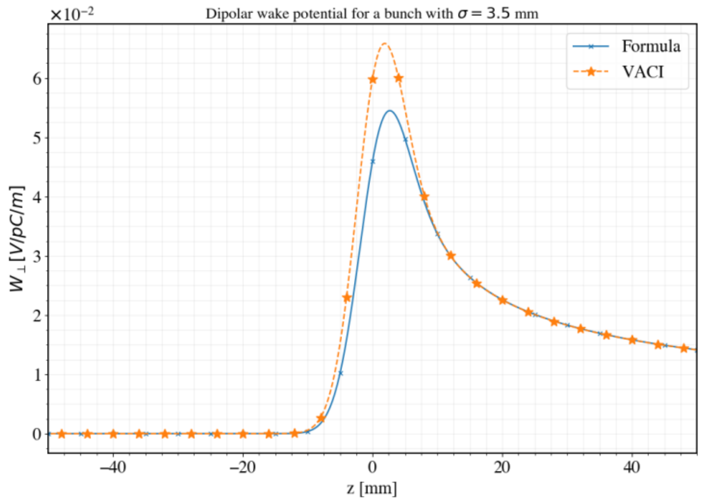
VACI results for FCC main ring

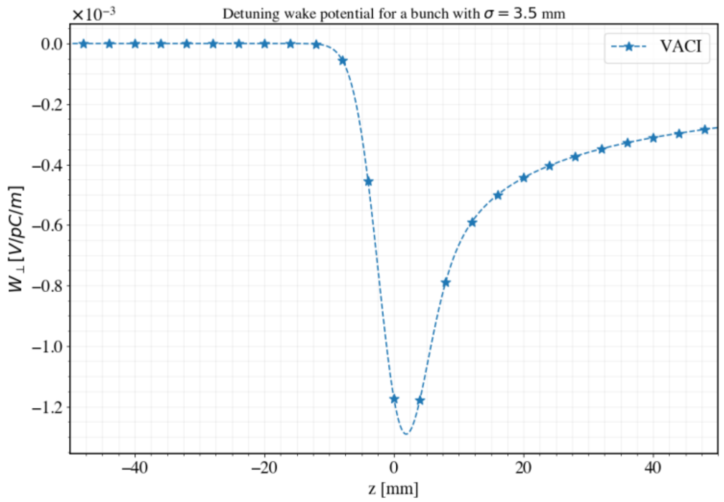
RW WakePotential

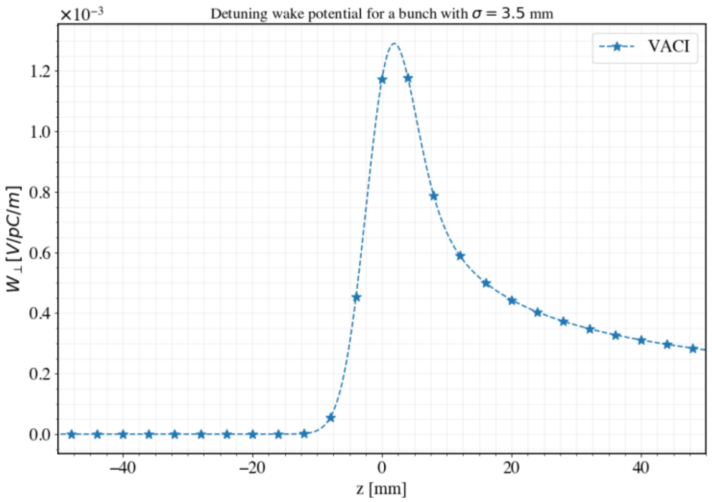
Copper Vacuum chamber
Length: 1m
NEG : 150 nm. $\sigma = 1.098e6$ s/m







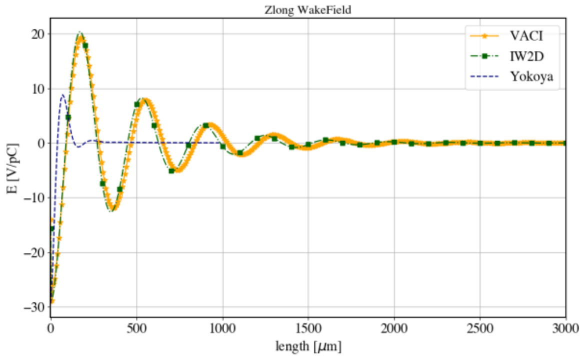


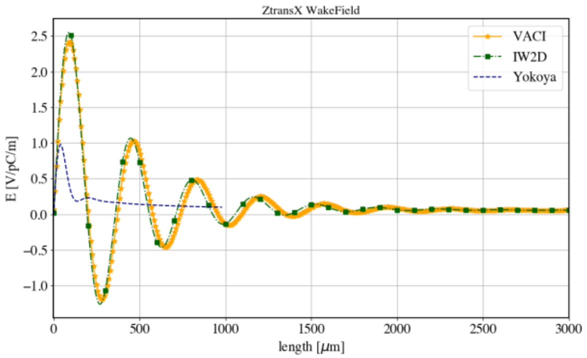


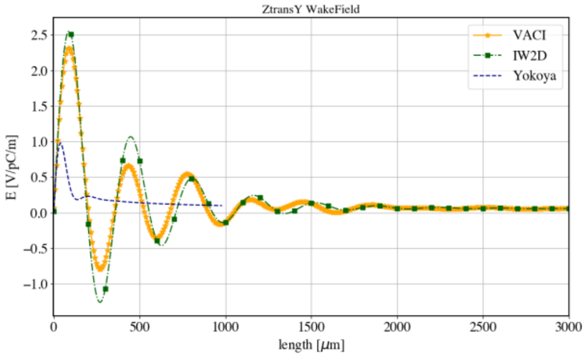
Possibility of reducing the radius of the FCC main ring chamber

35 mm → 30 mm

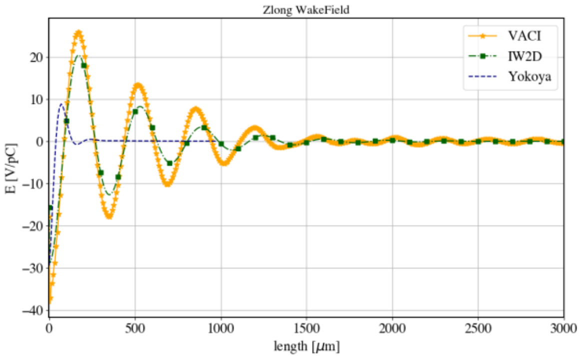
1. As a reference, IW2D simulations were conducted for a pipe with an R of 35 mm in both cases.
2. Yokoya's code result is for a single layer round pipe with R=35 mm.

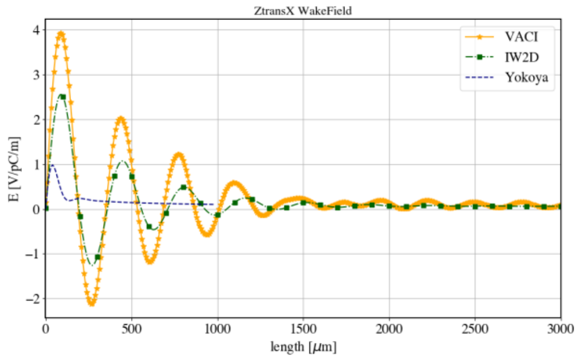


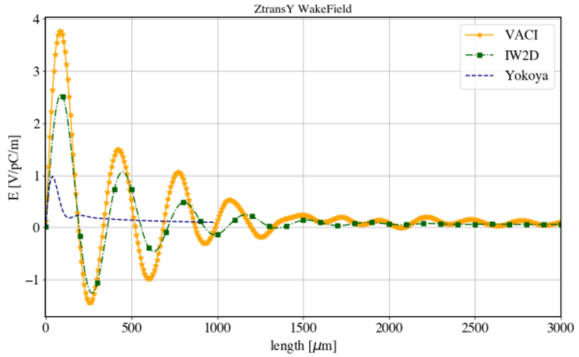




35 mm → 30 mm







Conclusion

I. The VACI suite, a 2D simulation code based on FEM for **resistive wall impedance**, has undergone significant updates and improvements.

II. The updates have resulted in increased simulation **accuracy** and **reduced calculation time**.

III. A **wake potential** solver has been added to the code, expanding its capabilities in studying beam dynamics.

IV. The results obtained from the VACI suite demonstrate excellent agreement with **analytical formulas** and established simulation codes like **IW2D**.

V. The VACI suite's enhanced accuracy and efficiency make it a valuable tool for investigating instabilities and threshold phenomena in beam dynamics.

Acknowledgements

Thank you

Rainer Wanzenberg

Thank you for your Attention

Your insights and perspectives are highly valued in further enhancing the code's functionality and efficiency. Please feel free to share it.

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