Resistive Wall Impedance in FCC Collider

Comparison of Simulation Codes

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FUTURE CIRCULAR COLLIDER

HELMHOLTZ

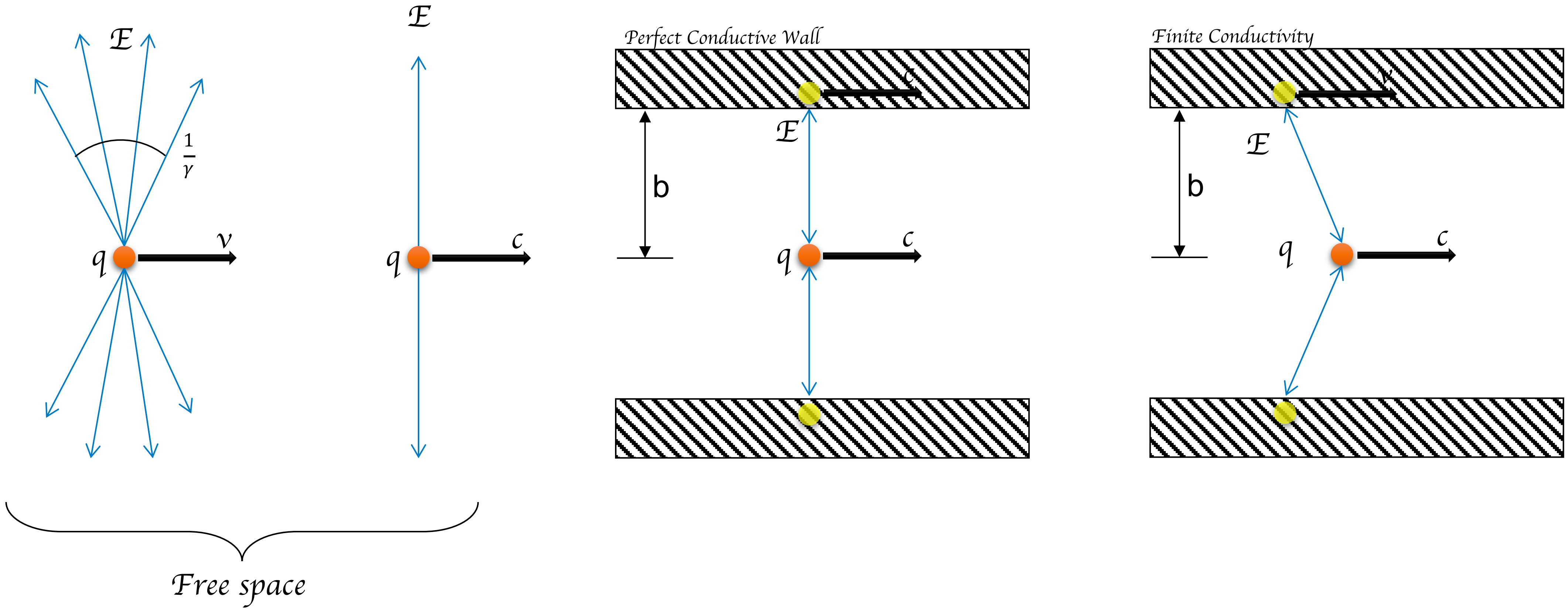
DESY.

Contents

Resistive Wall Impedance

Electromagnetic field carried by an ultra-relativistic point charge

A simplified concept of resistive wall wake field



Chao, Alexander Wu. "Physics of collective beam instabilities in high energy accelerators." *Wiley series in beam physics and accelerator technology* (1993)

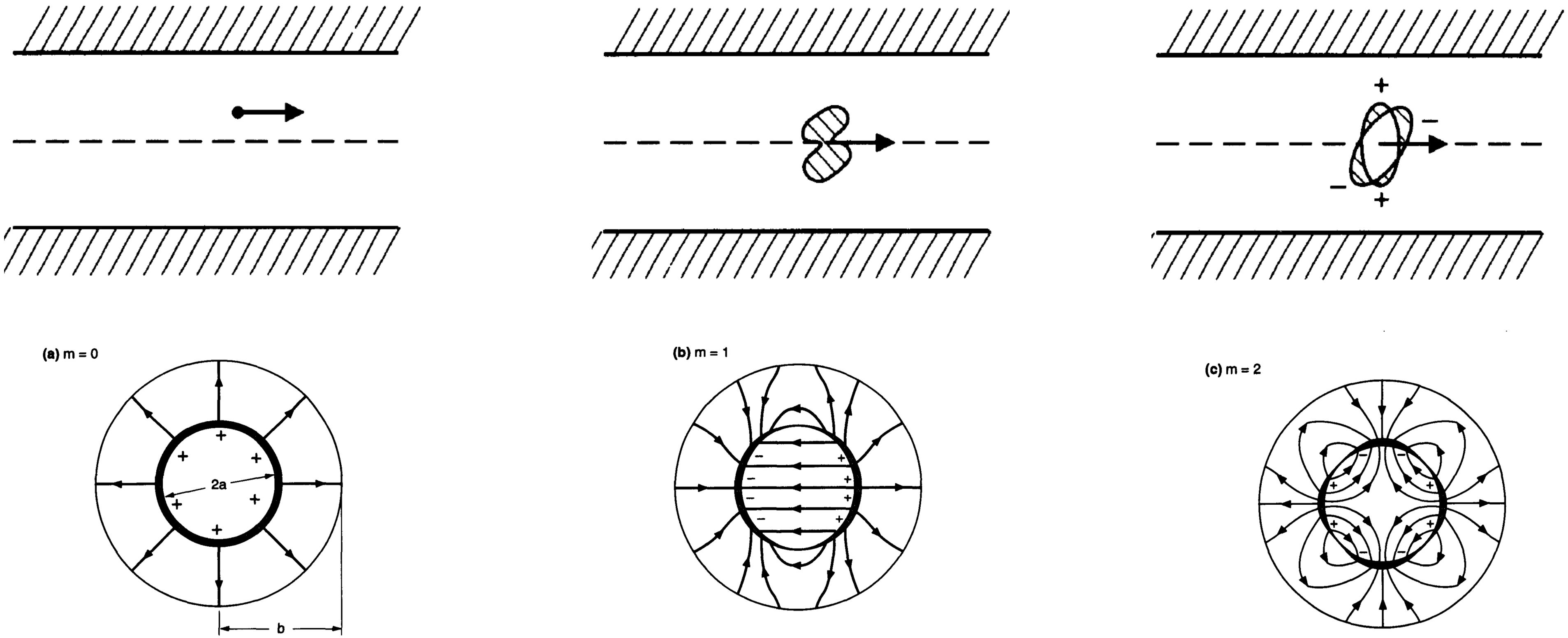
NEG coating

Why NEG is important

- To achieve ultra high vacuum (UHV) in accelerators people usually use Non-Evaporable Getter (NEG) coating on the inner side of vacuum chambers
- Many accelerators such as CERN LHC, ESRF, etc. utilize this method and they successfully reached to UHV.
- One of the NEG coating that I know is TiZrV ternary alloy (such as 30% Titanium, 30% Zirconium and 40% Vanadium).
- A typical conductivity of such chamber materials is around $\sigma = 1.098e6$ which is around ~50 times less than copper conductivity of $\sigma = 5.87e7$.
- NEG coating may increase the resistive-wall impedance of the machine significantly.

Electric Field patterns

Due to Monopole, Dipole and Quadrupole electron distribution



A mathematical approach to RW impedance

Solving maxwell's equations

Wake field (for uniform ring)

$$E_s = -\frac{16q}{b^2}\left(\frac{1}{3}e^u \cos\sqrt{3}\,u - \frac{\sqrt{2}}{\pi}\int_0^\infty dx \frac{x^2 e^{ux^2}}{x^6+8}\right),$$

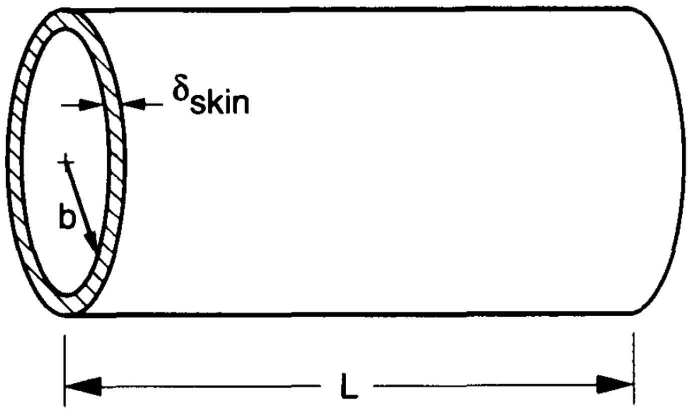
$$E_r = B_\theta = \frac{8qr}{(2\chi)^{1/3} b^3}\left(\frac{1}{3}e^u \cos\sqrt{3}\,u - \frac{1}{\sqrt{3}}e^u \sin\sqrt{3}\,u - \frac{\sqrt{2}}{\pi}\int_0^\infty dx \frac{x^4 e^{ux^2}}{x^6+8}\right)$$

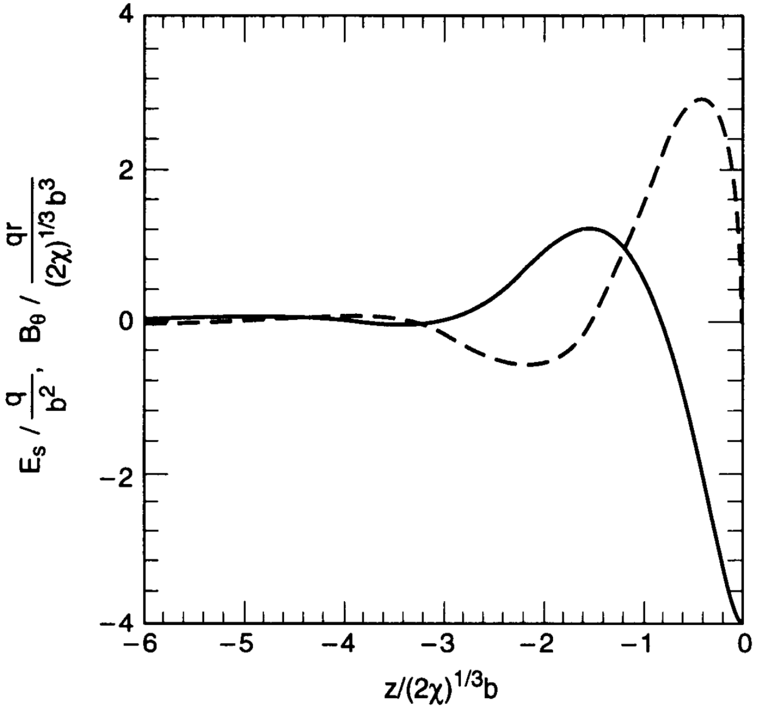
Wake Function

FFT

Resistive Wall Impedance (general form)

$$\frac{Z_m^{\parallel}(\omega)}{L} = \frac{\omega}{c}\frac{Z_m^{\perp}(\omega)}{L} = -\frac{1}{cI_m}A\left(\frac{\omega}{c}\right) = \frac{4/b^{2m}}{(1+\delta_{m0})bc\sqrt{\frac{2\pi\sigma}{|\omega|}}\,[1+\mathrm{sgn}(\omega)i] - \frac{ib^2}{m+1}\omega + \frac{imc^2}{\omega}}$$





Simulation Codes

Existing Simulation Codes

Maxwell Solvers vs Analytical Solvers

Maxwell's Equations solvers:

- ImpedanceWake2D by Mounet * (free)
- BeamImpedance2D by Niedermayer ** (free)
- Yokoya's Code *** (free)
- ECHO -1 / 2 / 3D code by Zagorodnov **** (free)
- CST Microwave Studio (commercially available)
- GDFIDL (commercially available)
- VACI Suite

Analytical formulas solvers:

- ReWall developed by Mounet et al CERN
- Numerical impedance calculations by Doliwa et al and Niedermayer
- Mathematica code developed in DESY
- CETA by Chao Li @ DESY for RW Impedance
- And …

* 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.

**** https://echo4d.de/

Introduction to VACI Suite

There is no passion to be found playing small - in settling for a life that is less than the one you are capable of living

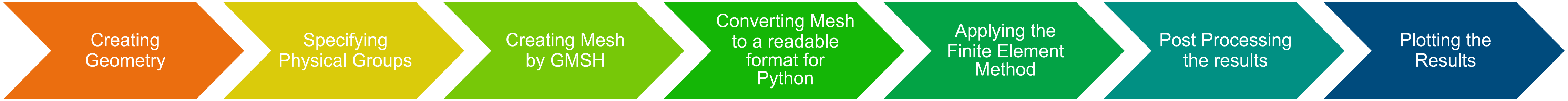
Nelson Mandela

VACI suite a versatile tool to calculate RW impedance

Introduction

VACI (VAcuum Chamber Impedance) suite

By coincidence it also means:
finding a balance that can restore the fun and enjoyment in your life.



How does VACI work?

Equations to solve

Maxwell's equations:

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

Material relations:

$$\begin{aligned} \vec{D} &= \varepsilon_c\vec{E}, \\ \vec{B} &= \mu\vec{H}, \end{aligned}$$

$$\begin{aligned} \varepsilon_c &= \varepsilon_0\varepsilon_1 = \varepsilon_0\left(\varepsilon_r' - j\varepsilon_r''\right) = \varepsilon_0\varepsilon_b\left[1 - j\tan\vartheta_E\right] + \frac{\sigma}{j\omega}, \\ \mu &= \mu_0\mu_1 = \mu_0\mu_r\left[1 - j\tan\vartheta_M\right]. \end{aligned}$$

Boundary Conditions:

BC for a metallic surface

$$\vec{n}\times\vec{n}\times\underline{\vec{E}} = \underline{Z}_s\vec{n}\times\underline{\vec{H}}$$

surface impedance

$$\underline{Z}_s = \frac{1}{\underline{Y}_s} = \frac{1+i}{\sqrt{2}}\sqrt{\frac{\omega\mu}{\kappa}}$$

Approaches to solve Maxwell's equations

1

$$\begin{cases} \nabla^2\vec{E} + \omega^2\varepsilon_c\mu\vec{E} = \dfrac{1}{\varepsilon_c}\vec{\mathrm{grad}}\rho_m + j\omega\mu\rho_m\upsilon\vec{e}_s. \\ \nabla^2\vec{H} + \omega^2\varepsilon_c\mu\vec{H} = \upsilon\dfrac{\partial\rho_m}{\partial r}\vec{e}_\theta - \dfrac{\upsilon}{r}\dfrac{\partial\rho_m}{\partial\theta}\vec{e}_r. \end{cases}$$

2

$$\begin{cases} \left[\Delta - \mu\varepsilon\dfrac{\partial^2}{\partial t^2}\right]\mathbf{A} = -\mu\mathbf{J} + \nabla\left[\nabla\cdot\mathbf{A} + \mu\varepsilon\dfrac{\partial\Phi}{\partial t}\right] \\ \left[\Delta - \mu\varepsilon\dfrac{\partial^2}{\partial t^2}\right]\Phi = -\dfrac{\rho}{\varepsilon} - \dfrac{\partial}{\partial t}\left[\nabla\cdot\mathbf{A} + \mu\varepsilon\dfrac{\partial\Phi}{\partial t}\right] \end{cases}$$

$$\nabla\cdot\mathbf{A} + \mu\varepsilon\frac{\partial\Phi}{\partial t} = 0$$

3

$$\begin{cases} \nabla\times\underline{\nu}\nabla\times\underline{\vec{E}} - \omega^2\underline{\varepsilon}\,\underline{\vec{E}} = -i\omega\underline{\vec{J}}_s \\ \nabla\cdot\underline{\varepsilon}\underline{\vec{E}}_{\mathrm{curl}} = 0 \ \text{ and } \ \nabla\times\underline{\vec{E}}_{\mathrm{div}} = 0 \end{cases}$$

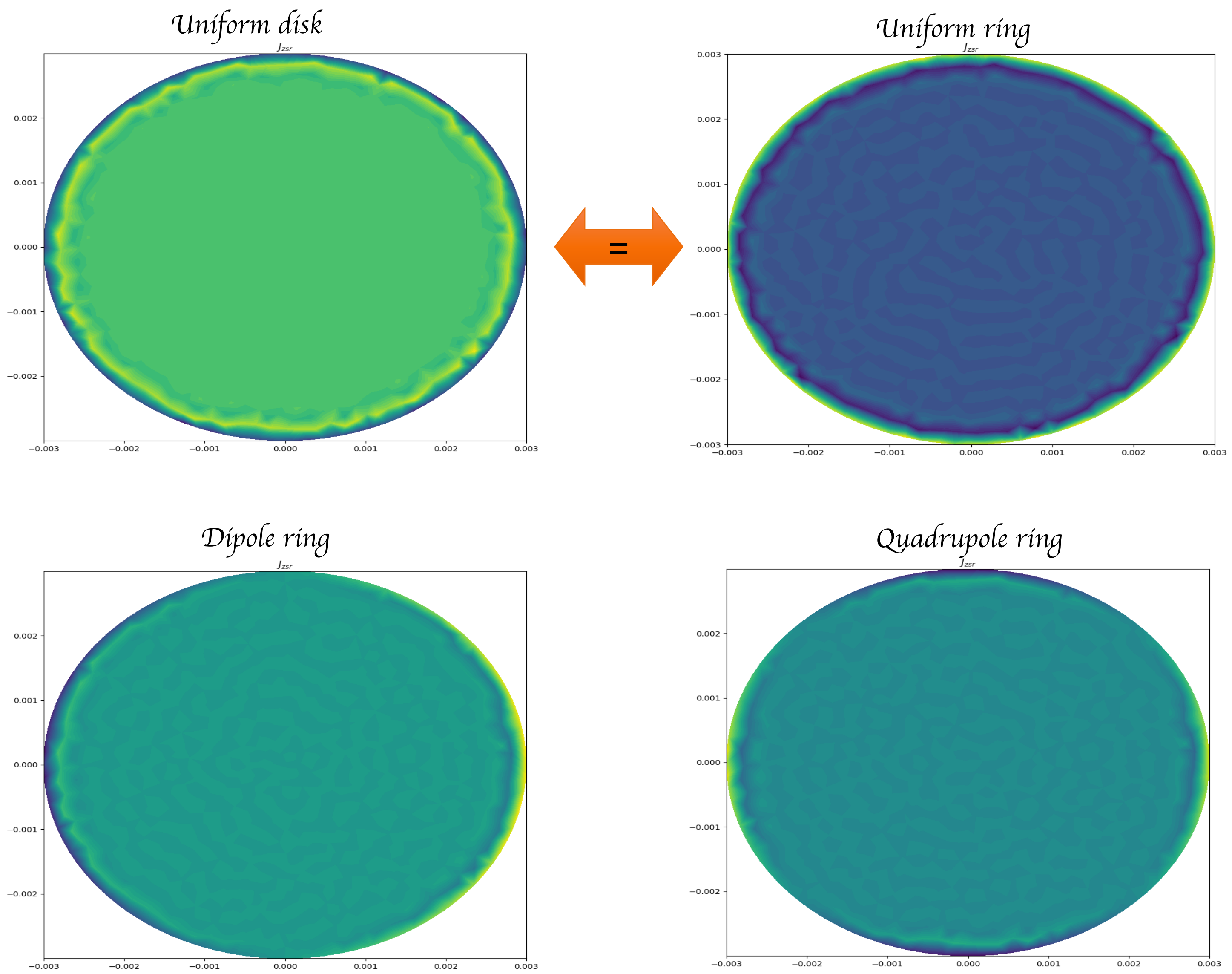
$$\underline{\vec{E}} = \underline{\vec{E}}_{\mathrm{curl}} + \underline{\vec{E}}_{\mathrm{div}}$$

Electron bunch distribution

Considering Higher Order Modes

For every geometry in VACI we can consider 3 modes for RW calculation:

- Monopole
- Dipole (Horizontal and vertical)
- Quadrupole



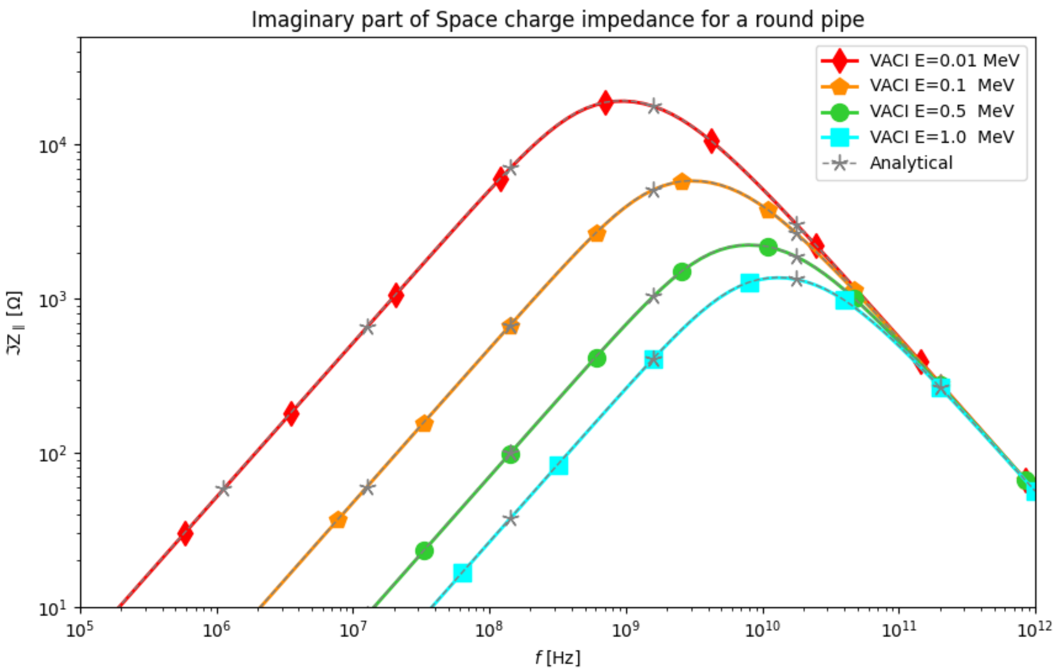
Possibilities and limitations:

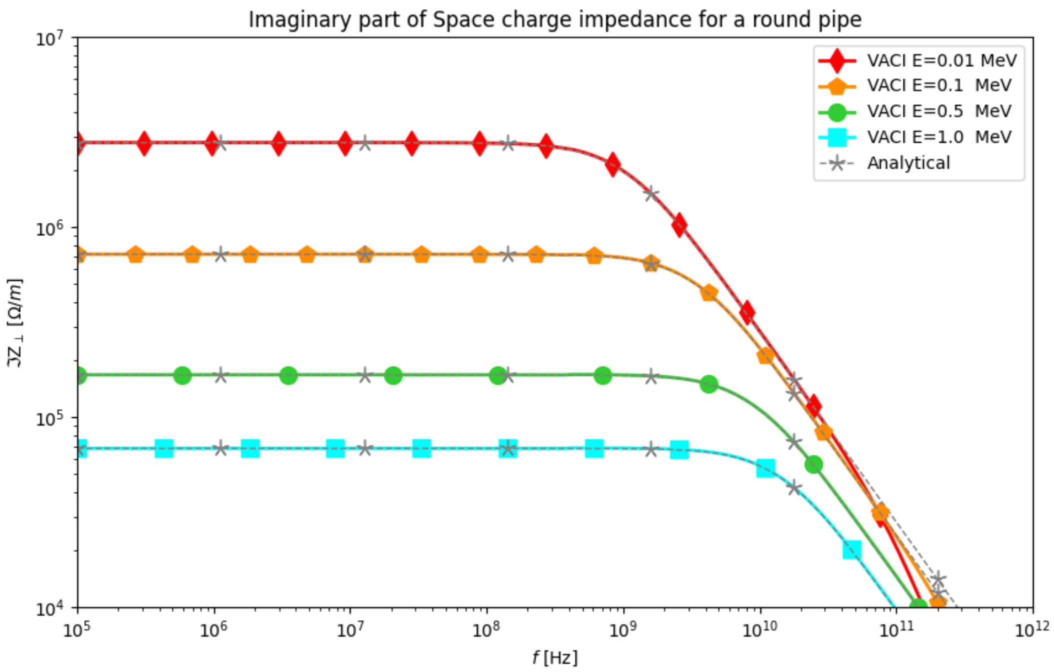
- The results are sensitive to mesh number so one should find a balance between calculation time and accuracy.
- For every distribution the impedance and wakefield can be calculated
- Bunch shape and location can be changed to also calculate weird configuration.
- The possibility of two bunches near each other is under consideration to be added to the code

VACI Results

VACI results for Space-Charge

Round pipe

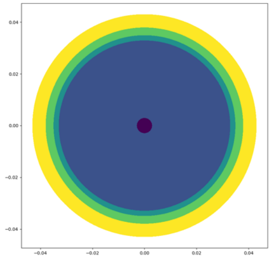


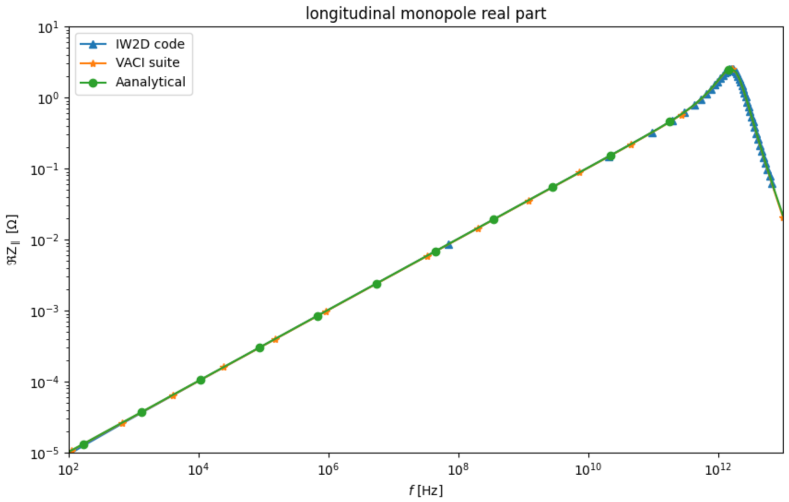


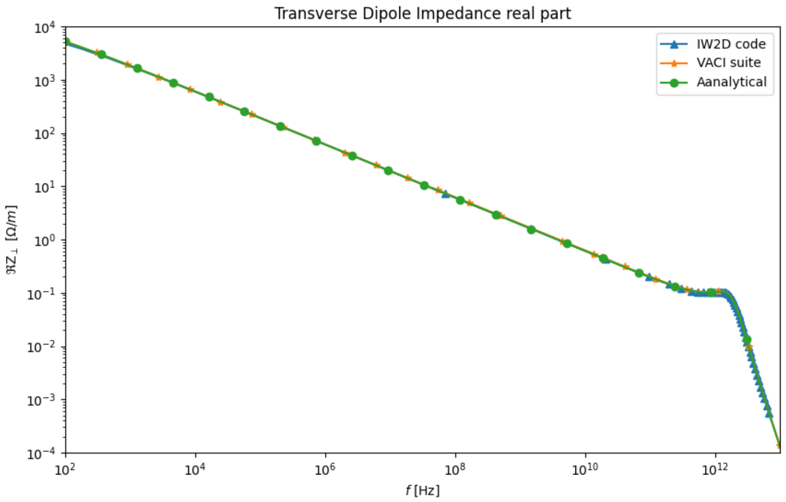
Gluckstern, Robert L. "Analytic methods for calculating coupling impedances." (2000).

VACI results for Round pipe

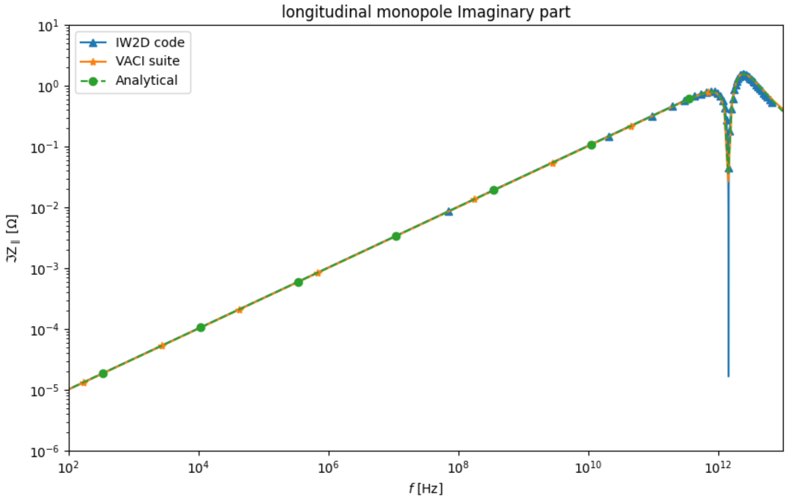
Impedance calculation

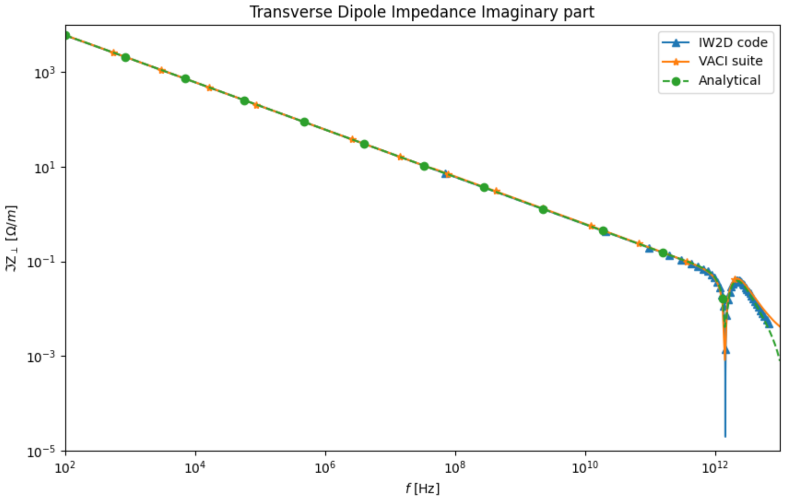






Energy: 15 GeV,
Round Pipe: r = 35 mm
Length = 1 m





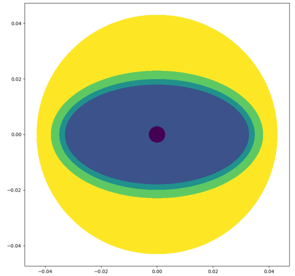
VACI results for Oval pipe

Impedance calculation

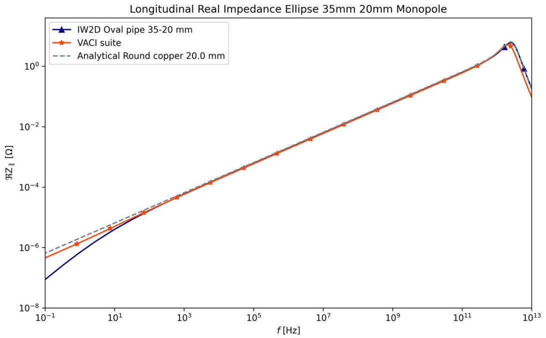
Energy: 15 GeV,
Ellipese pipe: r1 =35 mm– r2=20 mm,
Round Pipe: r = 20 mm

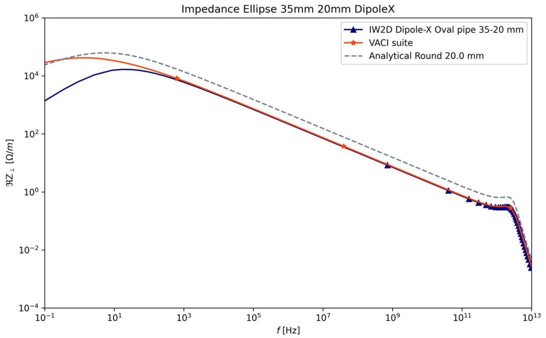
Yokoya's Factors:

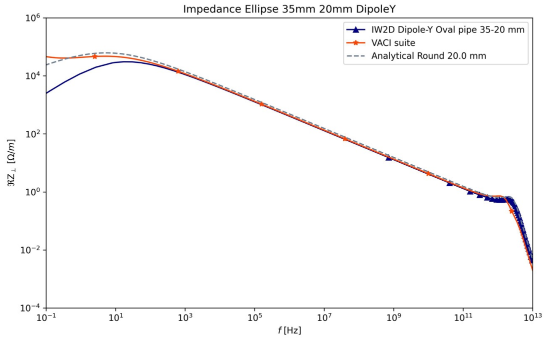
R [mm]	Long	X dip	Y dip	X quad	Y quad
20	0.953	0.458	0.839	-0.381	0.381

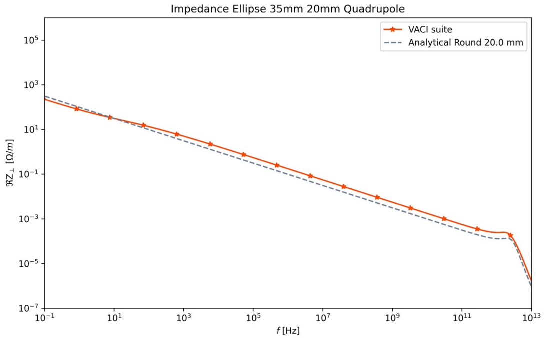


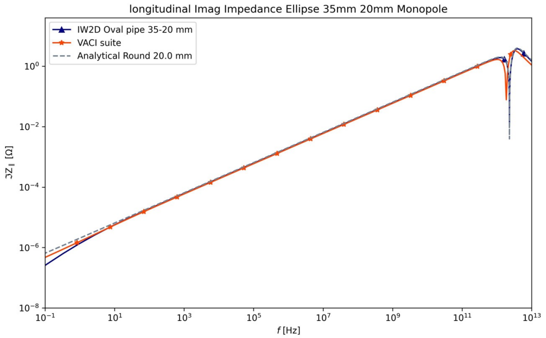
m_0 | m_{1h} | m_{1v} | m_2

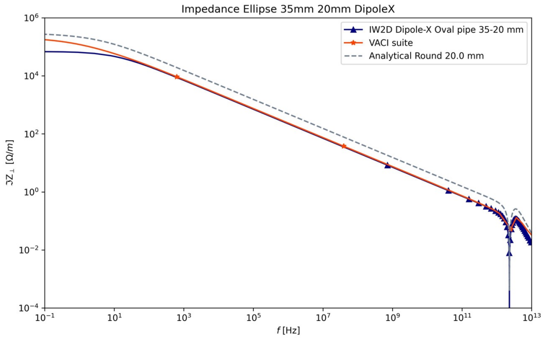


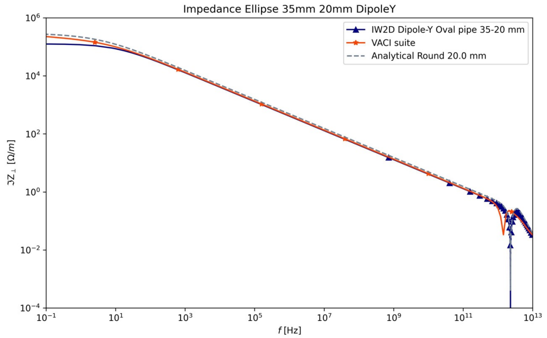


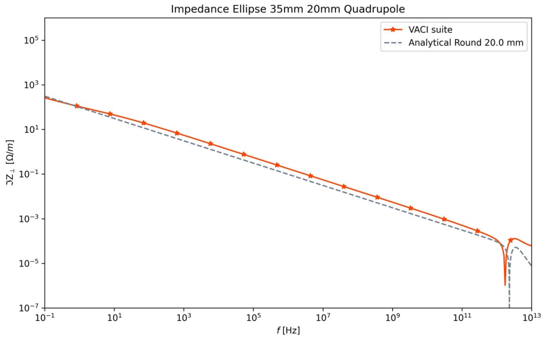












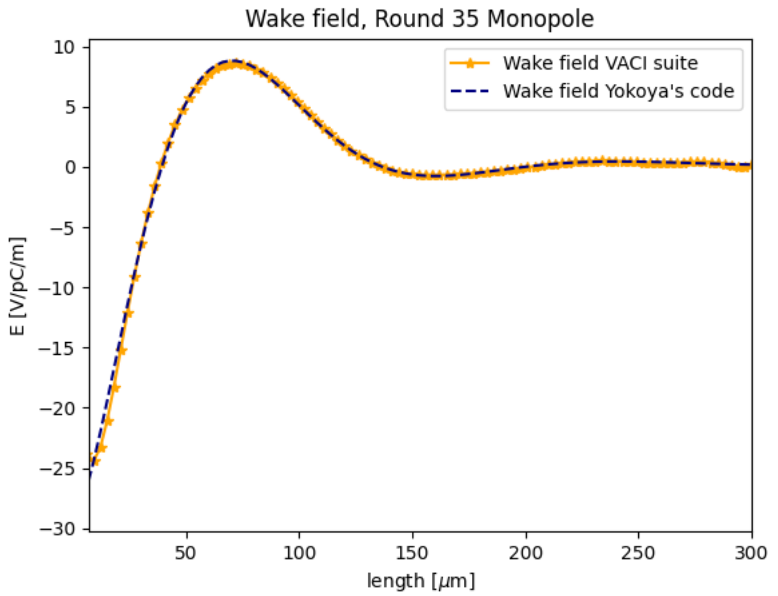
VACI also can give results in time domain

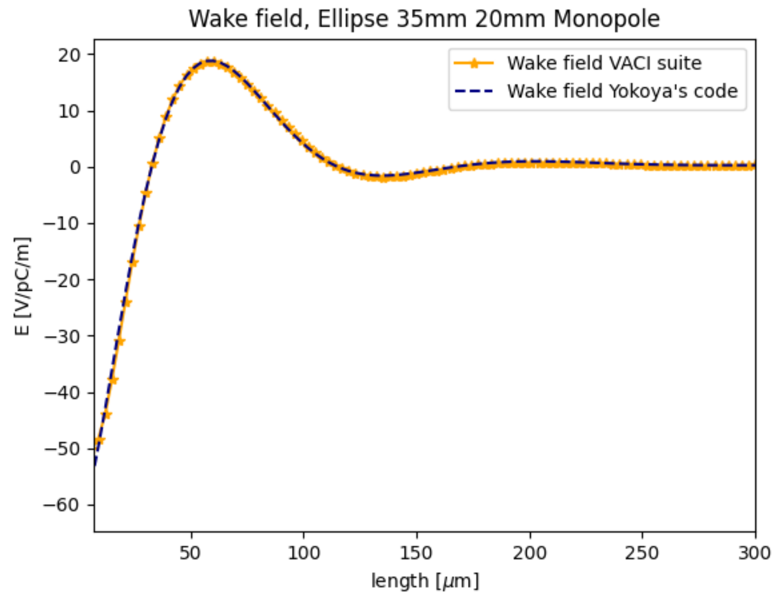
Longitudinal Wake field (E_z)

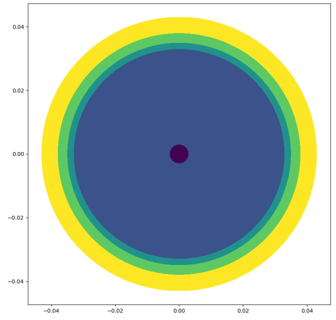
iFFT method:

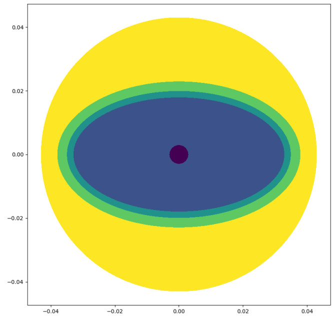
uneven sampling and a piecewise polynomial interpolation (cubic Hermite interpolation)

{Based on <u>*Nicolas Mounet*</u> Ph.D. thesis + some small upgrades}









Mounet, Nicolas. *The LHC transverse coupled-bunch instability*. No. THESIS. EPFL, 2012.

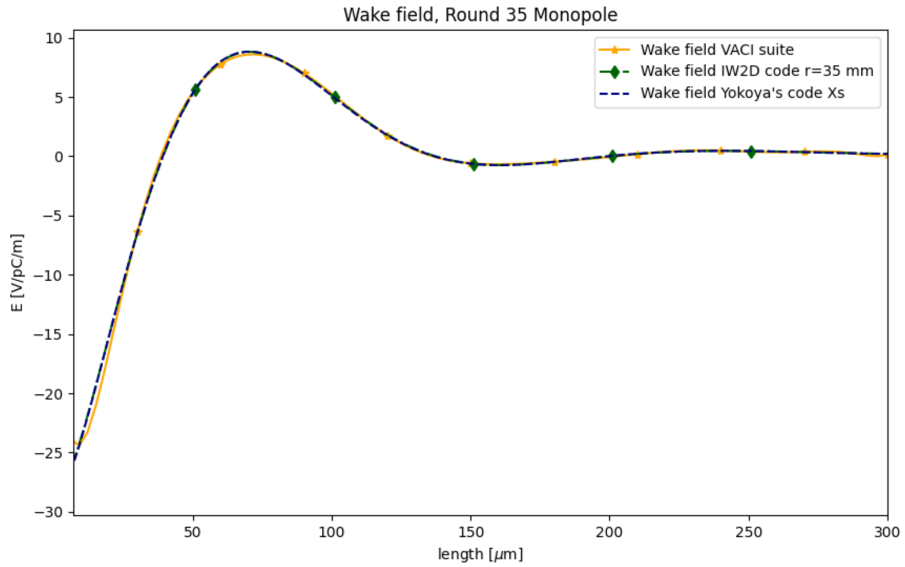
VACI also can give results in time domain

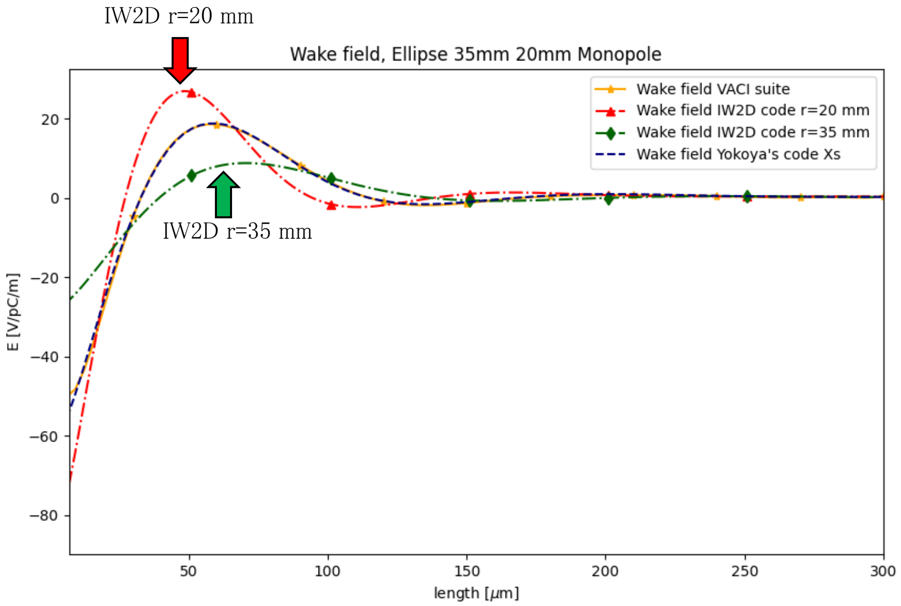
Longitudinal Wake field (E_z)

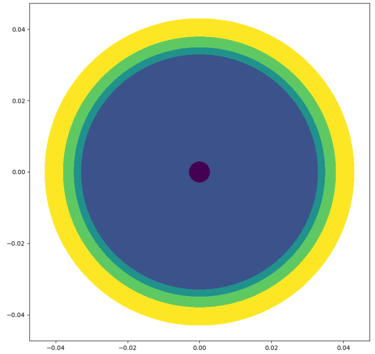
Energy: 15 GeV,
Ellipese pipe: r1 =35 mm– r2=20 mm,
Round Pipe: r = 20 mm

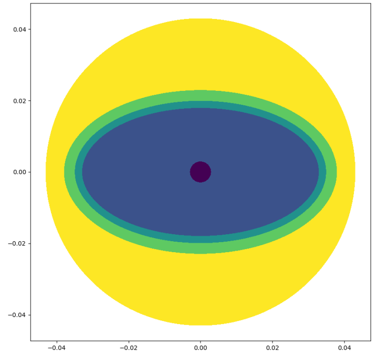
Yokoya's Factors:

R [mm]	Long	X dip	Y dip	X quad	Y quad
20	1	0.485	0.848	-0.362	0.362





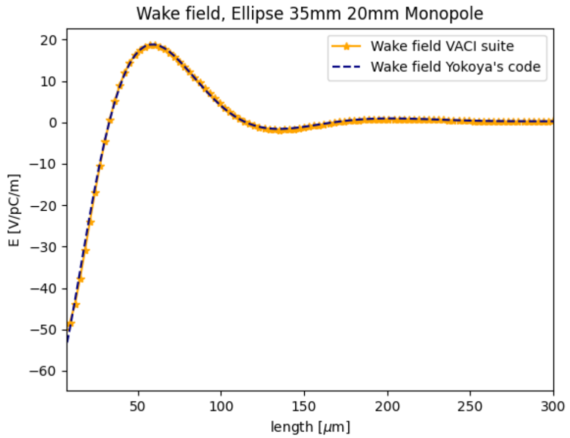




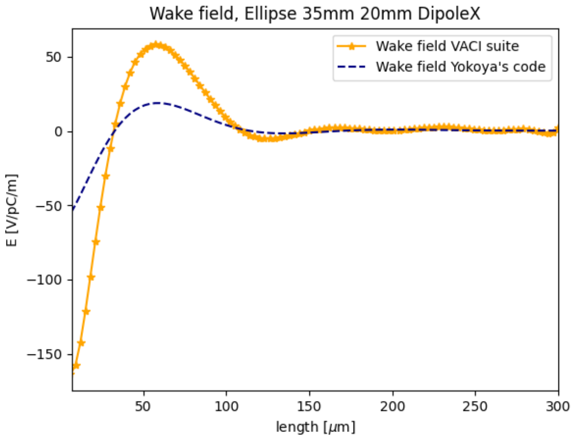
VACI Wake field calculation due to different bunch distributions

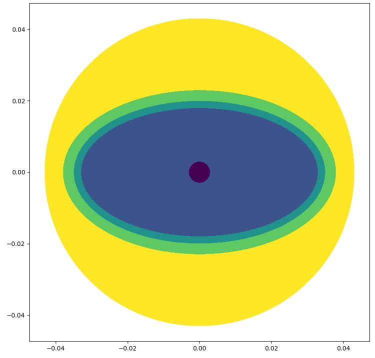
Only for E_z in Elliptical vacuum chamber, compared to Yokoya's result for Monopole E_z

Uniform ring

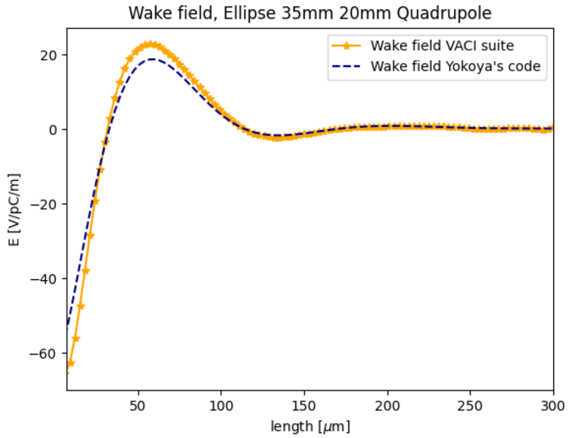


Ring with dipole dis. Hor.

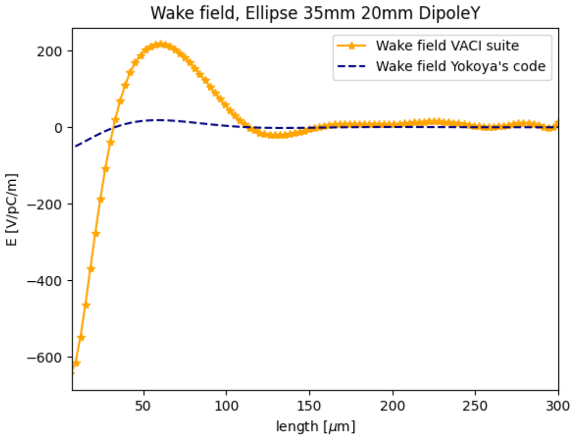




Ring with Quadrupole dis.



Ring with dipole dis. Ver.



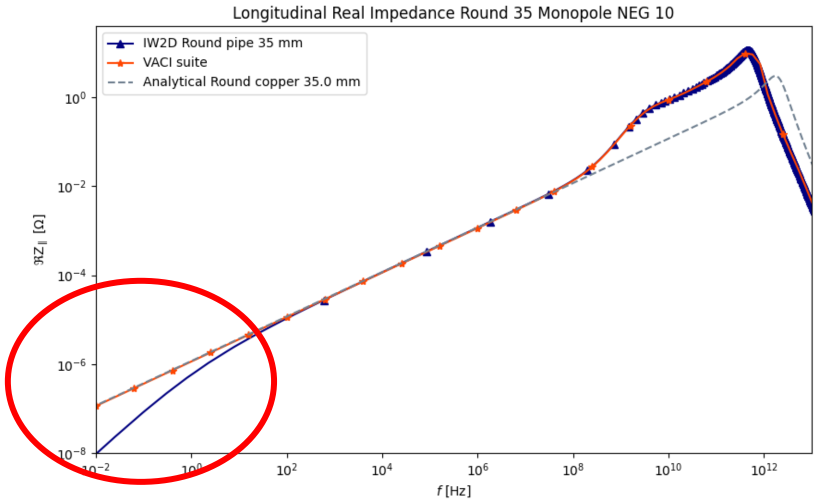
Panofskey−Wenzel theorem

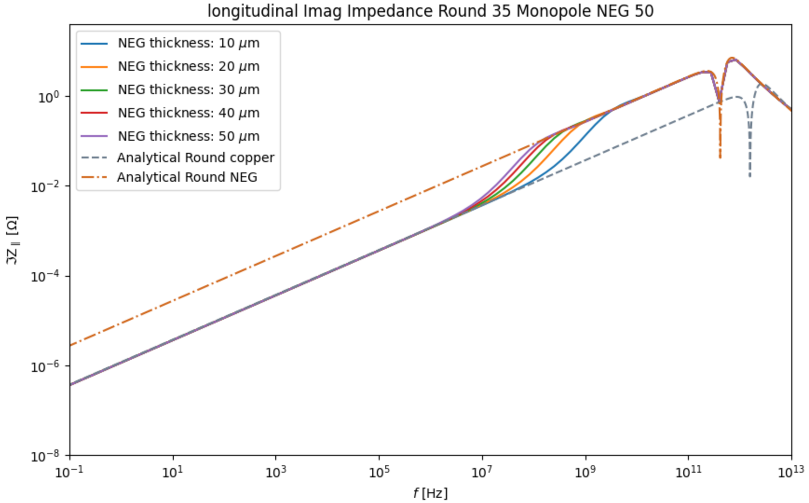
$$\nabla_\perp \vec{E}_z = \frac{\partial}{\partial z}\vec{E}_\perp$$

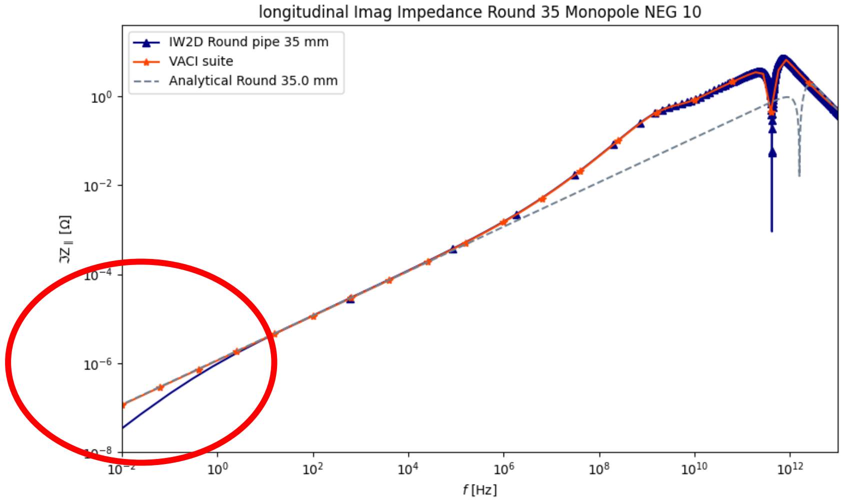
VACI results for Multi-Layer vacuum chamber

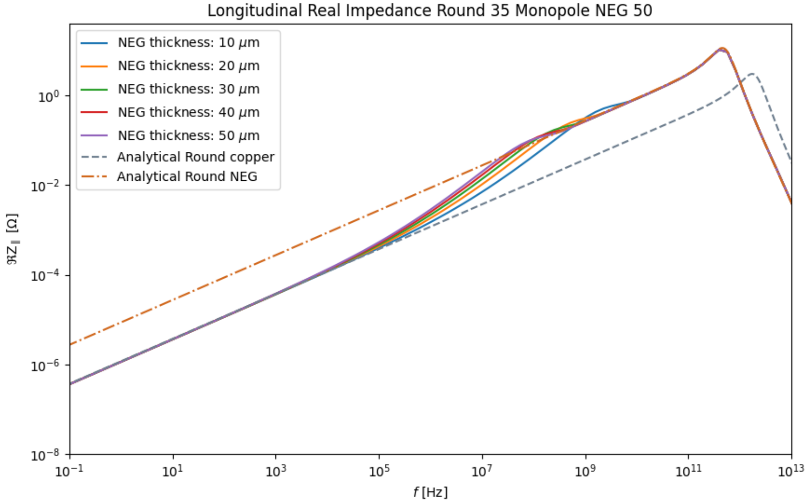
Impedance calculation of Round pipe With NEG coating

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









Resistive Wall Impedance of FCC main Ring

FCC booster and main rings Geometries

Impedance sources

Impedance Sources

I. Beam pipes and Resistive Wall Impedance

II. RF Cavities (No. 56 in a 4-cell array)

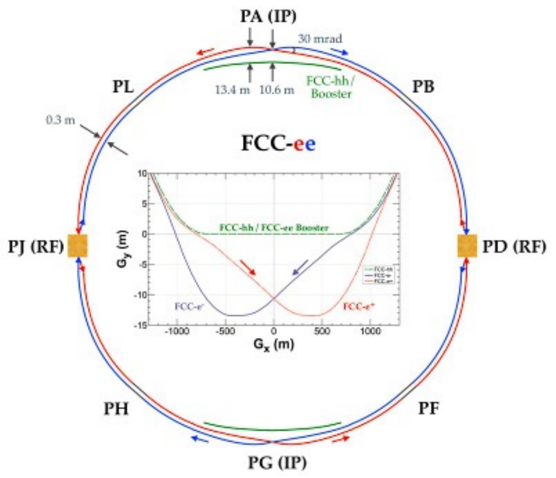
III. RF Cavity Tapers (No. 14 double tapers)

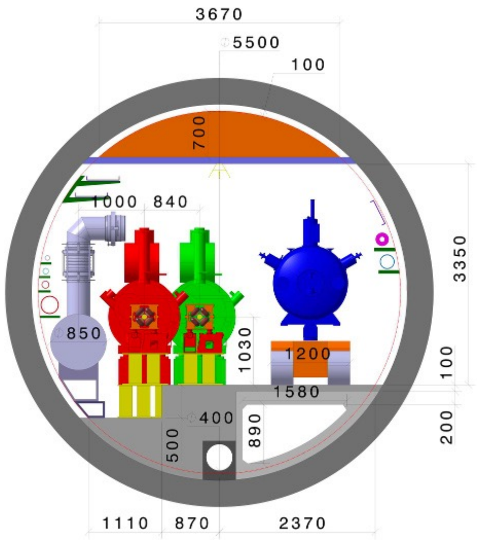
IV. Synchrotron Radiation (SR) absorbers

V. Collimators (No. 20)

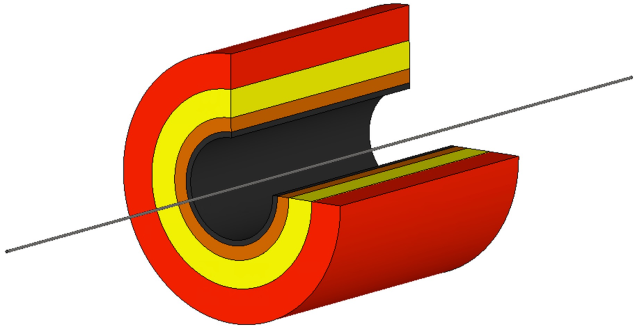
VI. Beam Position Monitors (No. 4000)

VII. Comb-Type RF shielding for bellows (No. 8000)

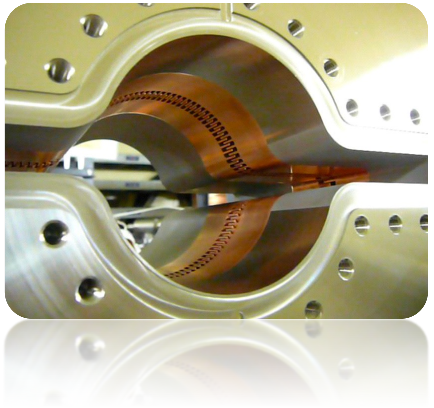




Booster ring

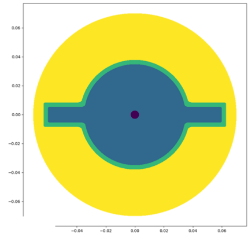


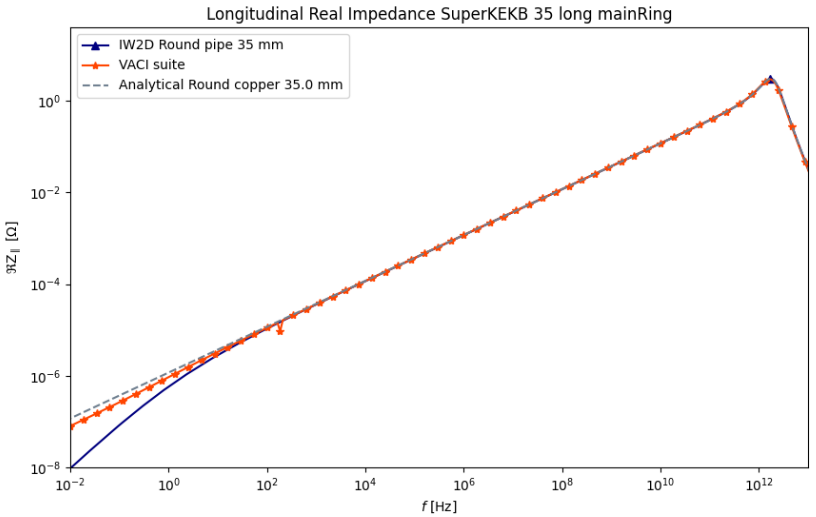
Main ring

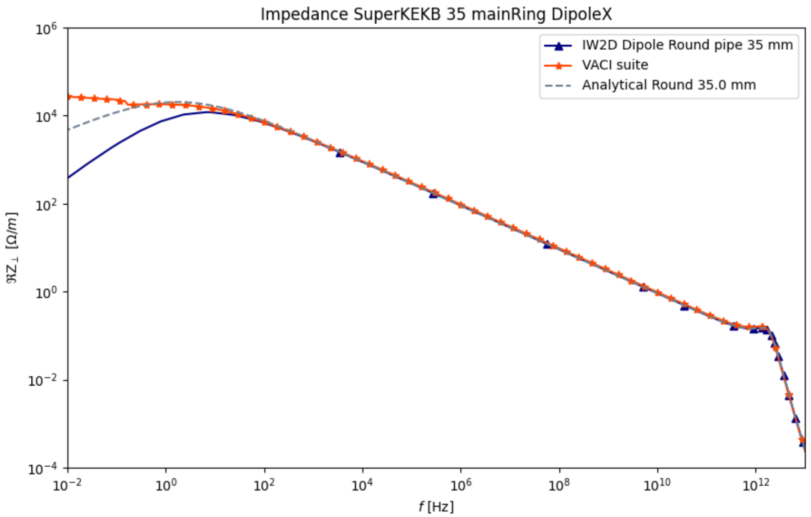


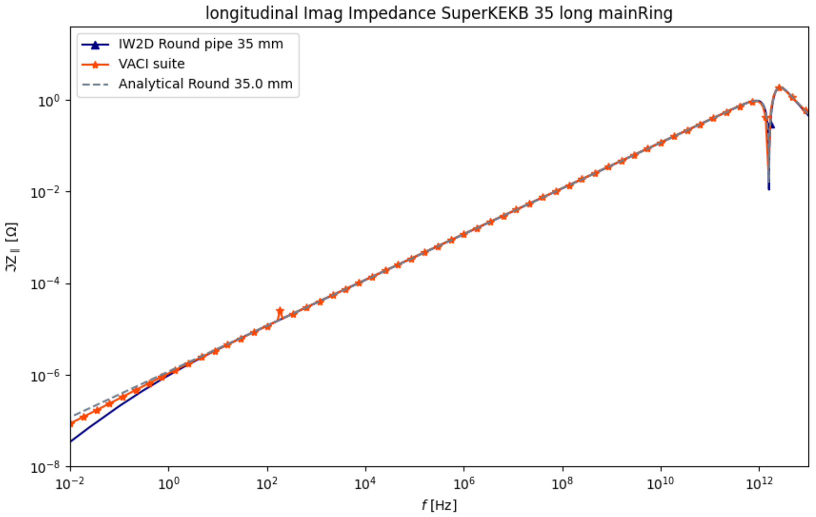
VACI results for FCC main ring

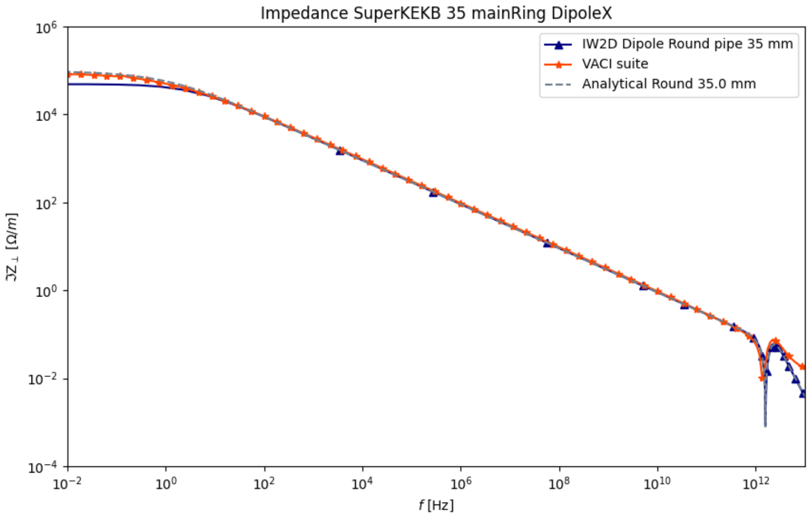
Impedance calculation (loglog plots)





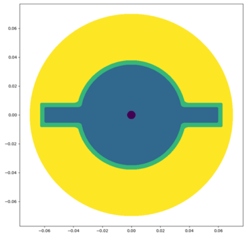




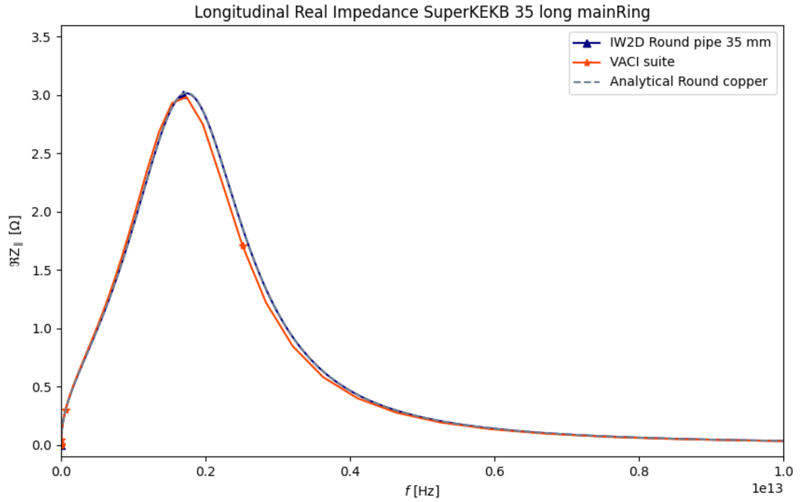


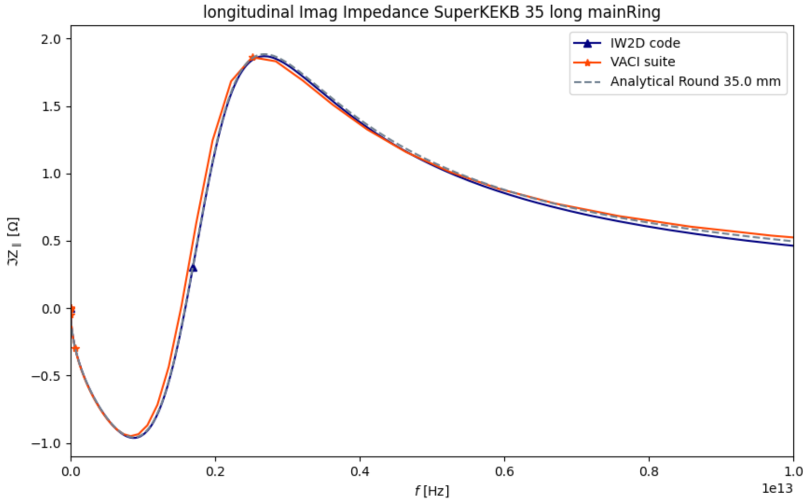
VACI results for FCC main ring

Impedance calculation (normal plots, 300 sample points)

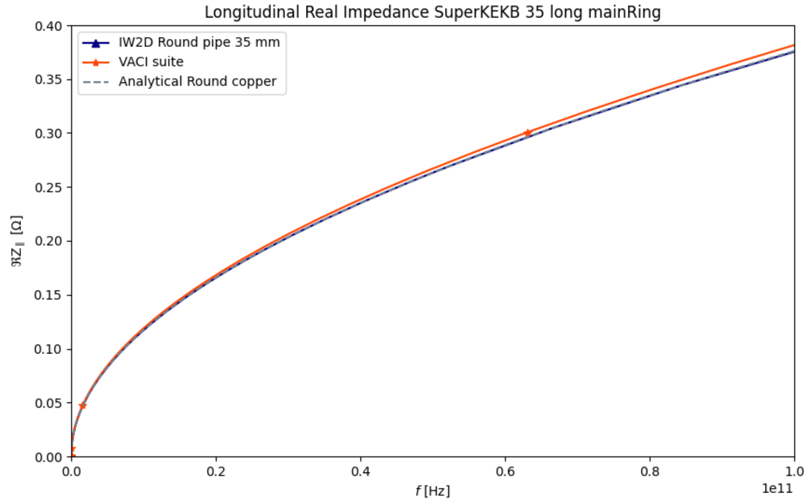


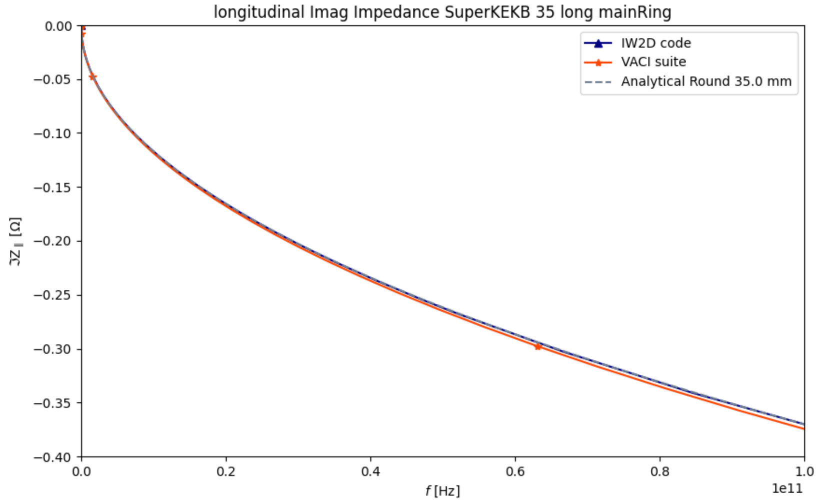
Frequency Range $[10^{-2}, 10^{13}]$





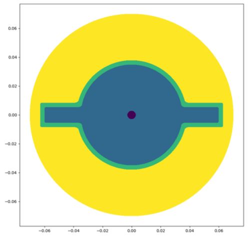
Frequency Range $[10^{-2}, 10^{11}]$



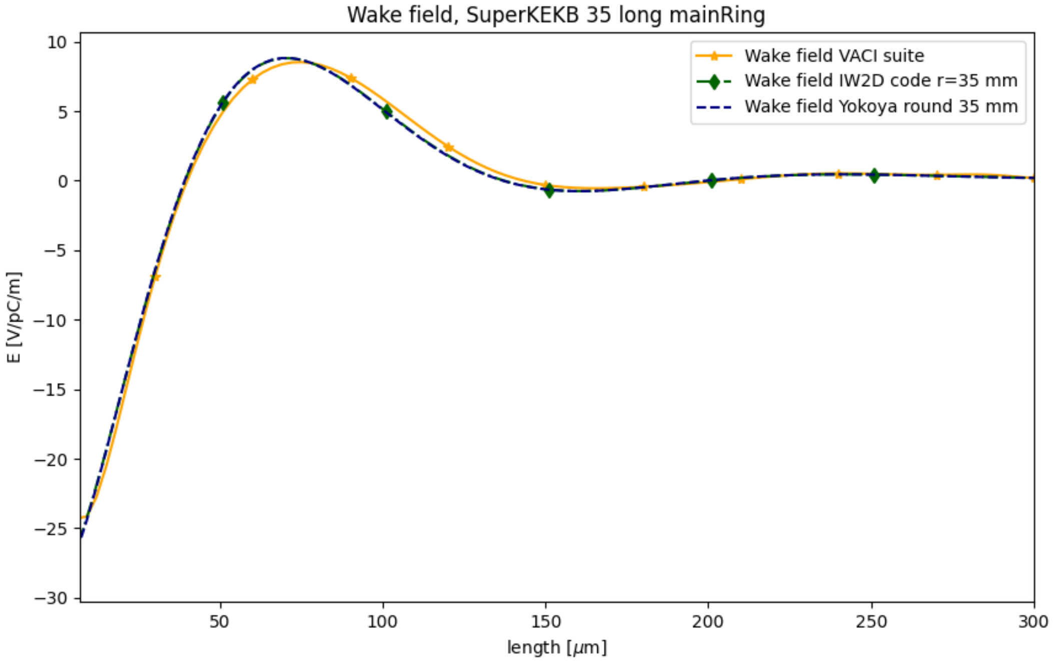


VACI results for FCC main ring

Wakefield calculation (normal plots, 300 sample points)



- Copper pipe without NEG coating
- Frequency Range $[10^{-2}, 10^{14}]$
- Energy: 15 GeV,
- Round Pipe for comparison: R = 35 mm
- iFFT method: uneven sampling and a piecewise polynomial interpolation



Summary and Outlooks

What we can expect…

What we have achieved:

- 2D RW impedance solver for vacuum chamber with general cross sections based on FEM
- RW impedance calculator with NEG coating
- Wake potential calculator
- Wake field calculator
- HOM impedance calculator
- Parallel on CPU, compiled for cluster.
- 3D geometries and CAD reader

Future plans

- Adding full ring impedance calculator
- Calculating impedance for two beam (injecting beam and existing beam)
- Adding 3D solver
- Maybe adding some simple 2D Geometrical impedance calculator

Thank you for your Attention

Please feel free to share any Ideas, discussion, suggestions?

Contact

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