Modelling of the FCC resistive wall impedance

A General Comparison on Simulation Codes for RW Impedance

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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FUTURE CIRCULAR COLLIDER Innovation Study

DESY.

Outline of talk:

1. Overview of machine parameters and FCC Booster and Impedance Budget
2. Resistive Wall impedance
3. Impedance simulation codes
4. General Comparison of simulation codes' results
5. Introduction to "VACI-Suite"

Overview of machine parameters, FCC Booster, and Impedance Budget

Resistive Wall impedance

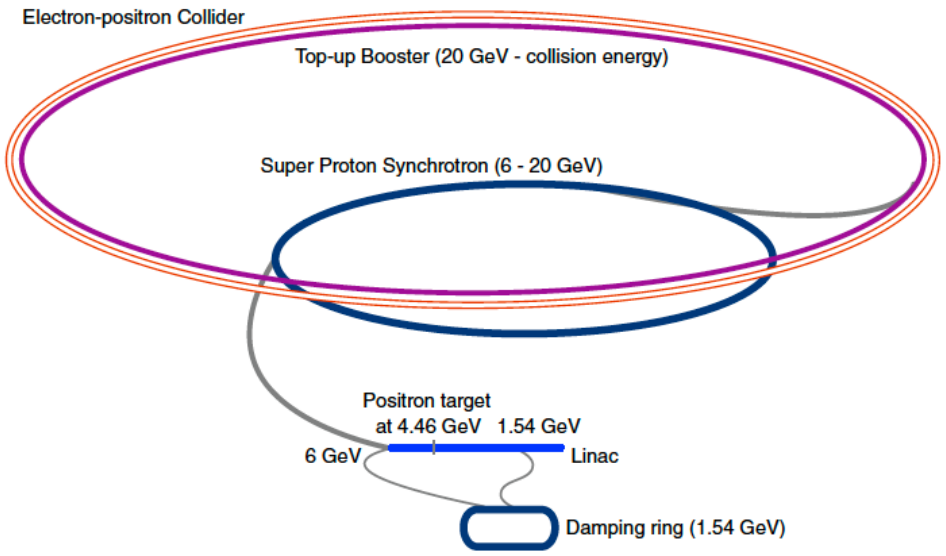
Impedance simulation codes

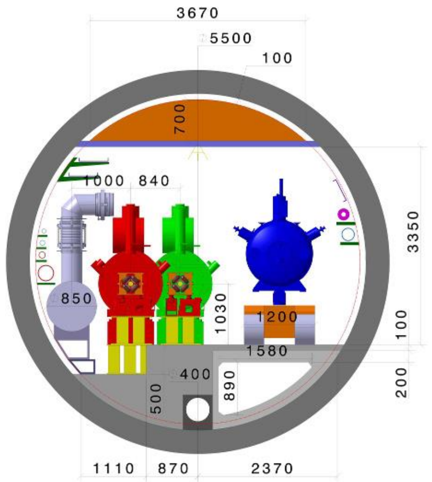
General Comparison of simulation codes’ results

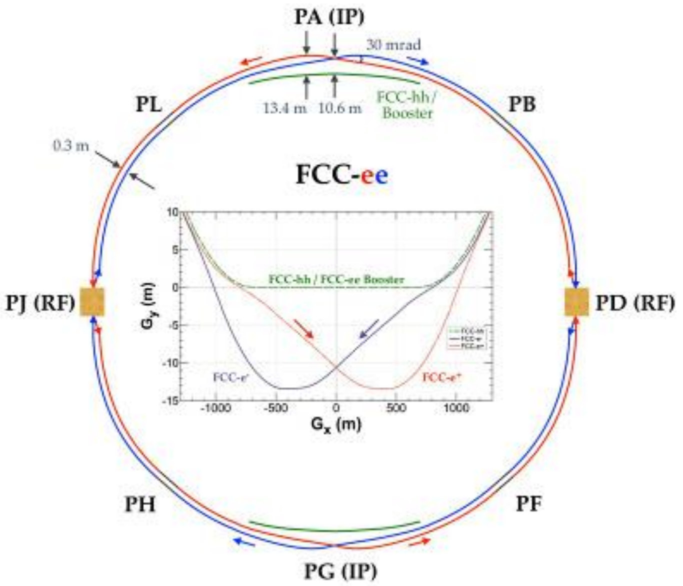
Introduction to “VACI-Suite”

Main information regarding Top-Up booster

lattice elements based on the FCC CDR report







- The booster ring lattice design is similar to the main ring in the same tunnel.
- Calculations will use the information of the main ring, for example:
  - ❖ Length of the ring
  - ❖ Length of each element
  - ❖ Number of elements,
  - ❖ Geometry of the elements
  - ❖ And …

Based on the CDR, Resistive wall impedance is the major source of the coupling impedance

Coupling impedance sources in the main ring based on CDR

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)

Table 2.8. Power loss contribution of the main FCC-ee vacuum chamber components at nominal intensity and bunch length, in the lowest energy case of 45.6 GeV.

Component	Number	k_l (V/pC)	P_l (MW)
Resistive wall	97.75 km	210	7.95
RF cavities	56	18.5	0.7
RF double tapers	14	26.6	1.0
Collimators	20	18.7	0.7
Beam position monitors	4000	40.1	1.5
Bellows	8000	49	1.8
Total		362.9	13.7

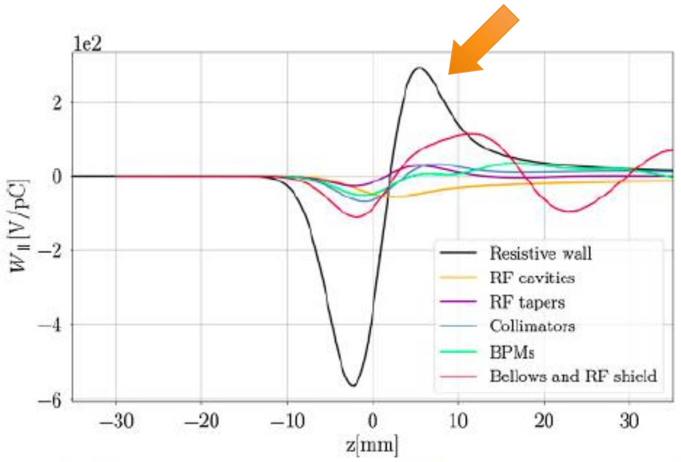
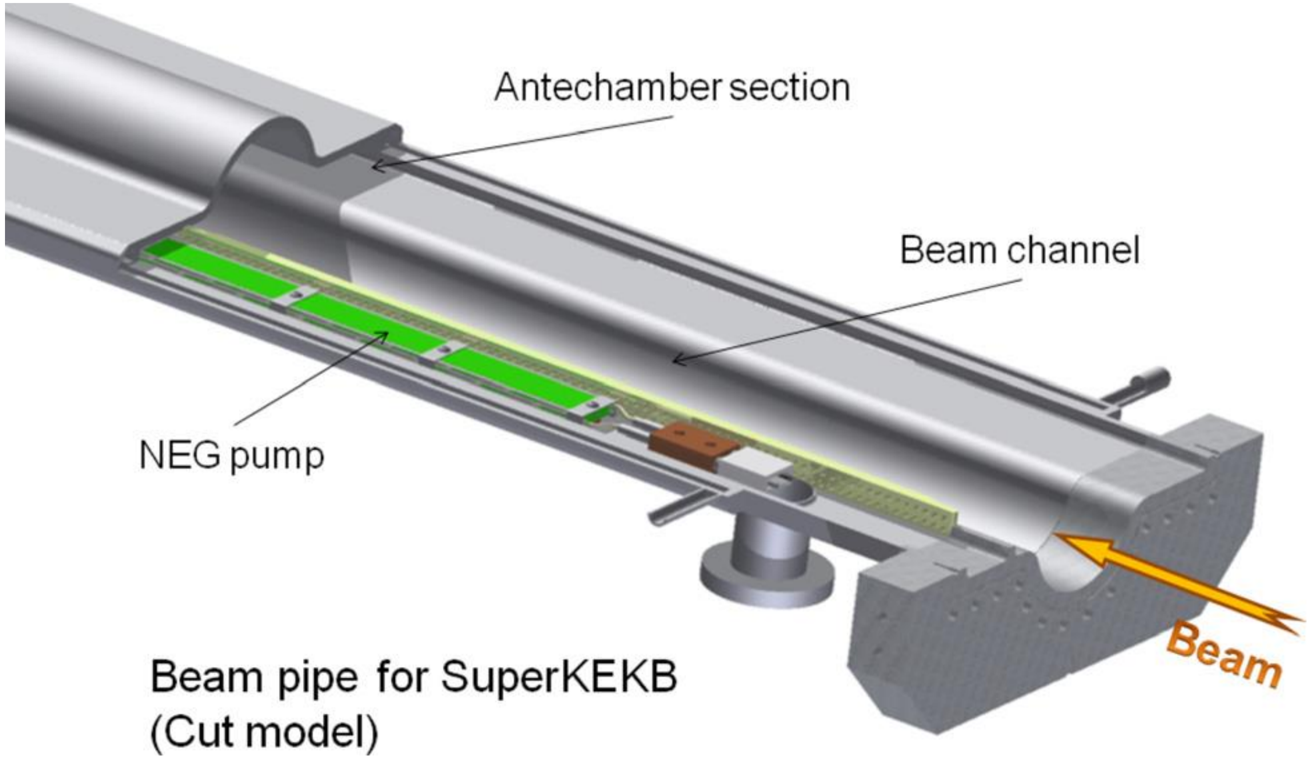


Fig. 2.26. Longitudinal wake potentials for the nominal bunch length $\sigma_z = 3.5$ mm without beamstrahlung due to main vacuum chamber components compared with the RW contribution (black line).

Beam pipes are the major source of the Resistive Wall impedance

Design of the beam pipe based on SUPERKEKB with NEG coating

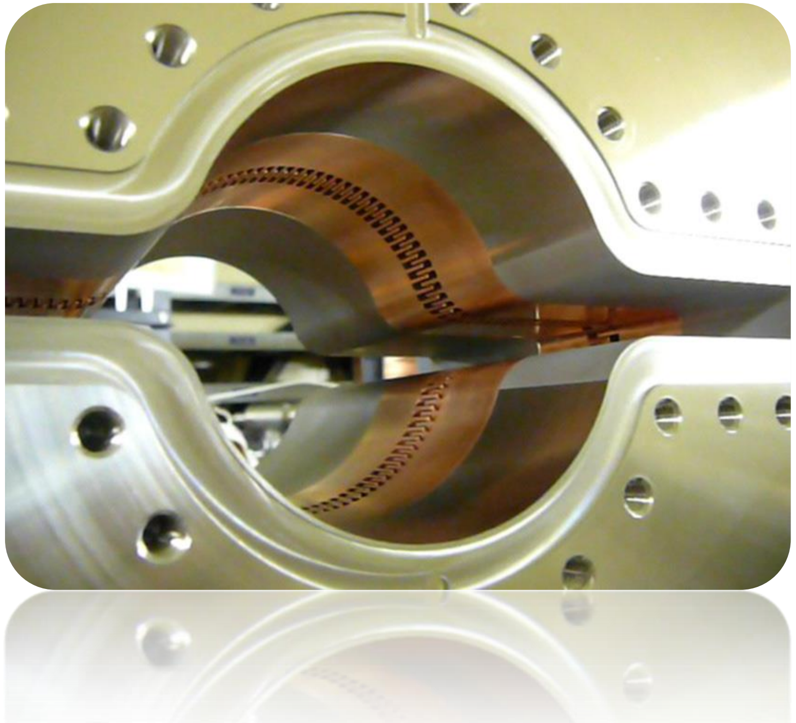


J. Vac. Sci. Technol. A, Vol. 30, No. 3, May/Jun 2012

The major source of the Resistive Wall impedance is the beam pipe with a length *approximately* equal to the ring circumference (~97 km).

The pipe cross section is similar to the pipe used in SUPERKEKB with a NEG coating.

NEG coating on the walls of the pipe has a huge impact on the RW impedance.
(for example check: PHYS.REV.ACCEL.BEAMS21,041001(2018).



Overview of machine parameters, FCC Booster, and Impedance Budget

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RW Theory

For a point like charge

1. The RW impedance for single-layer <u>round</u> vacuum chamber:

Wakefield →

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

K. Bane SLAC/AP 1991

Impedance →

$$\frac{Z_m^{\parallel}(\omega)}{L} = \frac{\omega}{c}\frac{Z_m^{\perp}(\omega)}{L} = -\frac{1}{cI_m}A\left(\frac{\omega}{c}\right)$$

$$= \frac{4/b^{2m}}{(1+\delta_{m0})bc\sqrt{\frac{2\pi\sigma}{|\omega|}}[1+\mathrm{sgn}(\omega)i] - \frac{ib^2}{m+1}\omega + \frac{imc^2}{\omega}}.$$

Physics of Collective Beam Instabilities in High Energy Accelerators
By <u>Alexander Wu Chao</u> · 1993

2. The RW impedance for multi-layer <u>round</u> vacuum chamber :

$$Z_{\parallel}^{(n)} = -\frac{E_z^o}{e} = -\frac{1}{e}\tau\, I_n(\lambda r) D_2 \cos(n\varphi) - \frac{E_z^\infty}{e}\cos(n\varphi). \quad \& \quad \nabla_\perp Z_\parallel^{(n)} = k_c \vec{Z}_\perp^{(n)}$$

Investigation of the PETRA III Resistive Wall Impedance
Internal Report DESY M 07-01
September 2007
M. Ivanyan et. Al.,

Where D2 determines by azimuthal magnetic field, $I_n(x)$ is a modified Bessel function of the first kind and $\tau = \gamma^{-1}$

Results of PETRA III resistive wall impedance study

NEG coated round chamber

- The RW impedance for multi-layer round vacuum chamber :

$$Z_{\parallel}^{(n)} = -\frac{E_z^o}{e} = -\frac{1}{e}\tau\, I_n(\lambda r) D_2 \cos(n\varphi) - \frac{E_z^\infty}{e}\cos(n\varphi).$$

Investigation of the PETRA III Resistive Wall Impedance
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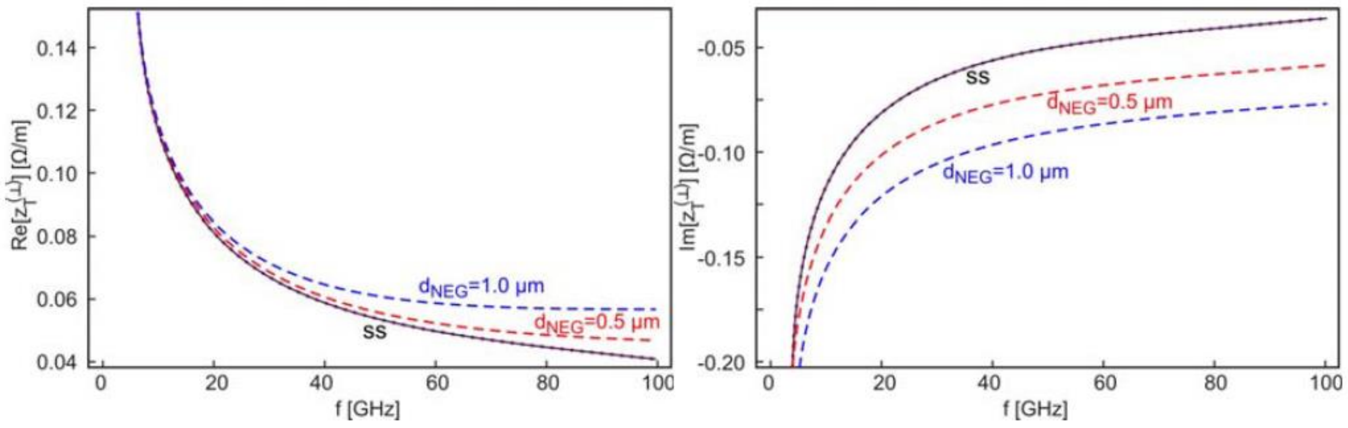

Real and imaginary parts of the transverse dipole impedance for a stainless steel tube with an inner radius of 47 mm (wall thickness 2 mm) with an inner NEG coating, which is 1 μm and 0.5 μm thick. The impedance of a stainless steel (SS) tube without coating is also shown

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Simulation Codes

Maxwell Solvers vs Analytical Solvers

Maxwell's Equations solvers:

- ImpedanceWake2D by Mounet *
- BeamImpedance2D by Niedermayer **
- Yokoya's Code ***
- ECHO -1 / 2 / 3D code by Zagorodnov ****
- CST Microwave Studio
- GDFIDL

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/

Overview of machine parameters, FCC Booster, and Impedance Budget

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How does Yokoya's code work?

For Single-Layer Pipe

The **boundary element method** (BEM) solver

- The numerical algorithm is Boundary Element method, a numerical computational method of solving linear partial differential equations which have been formulated as integral equations (i.e. in boundary integral form).

$$E_z(\mathbf{r}) = \oint ds' \left[-ik(Z_0 H_\tau - E_n) G(\mathbf{r}, \mathbf{r}') - E_z \mathbf{n}' \cdot \nabla'_\perp G(\mathbf{r}, \mathbf{r}')\right]$$

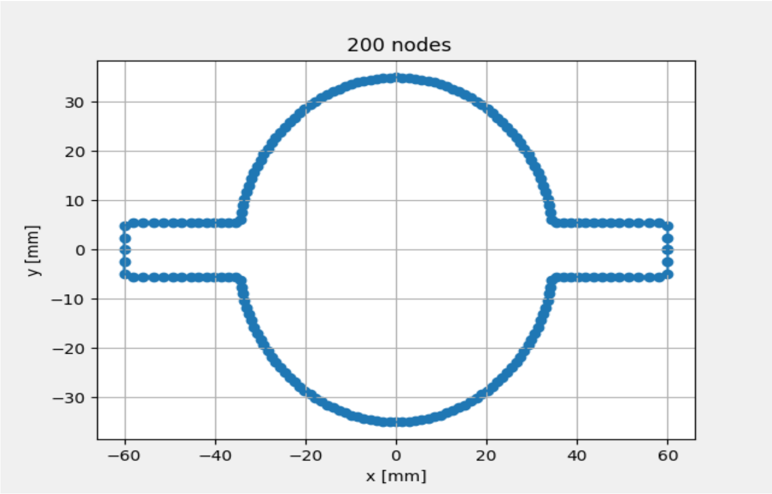
$$G(\mathbf{r}, \mathbf{r}') = -\frac{1}{2\pi} \log |\mathbf{r} - \mathbf{r}'|, \qquad \nabla'_\perp G(\mathbf{r}, \mathbf{r}') = \frac{1}{2\pi} \frac{\mathbf{r} - \mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|^2}.$$

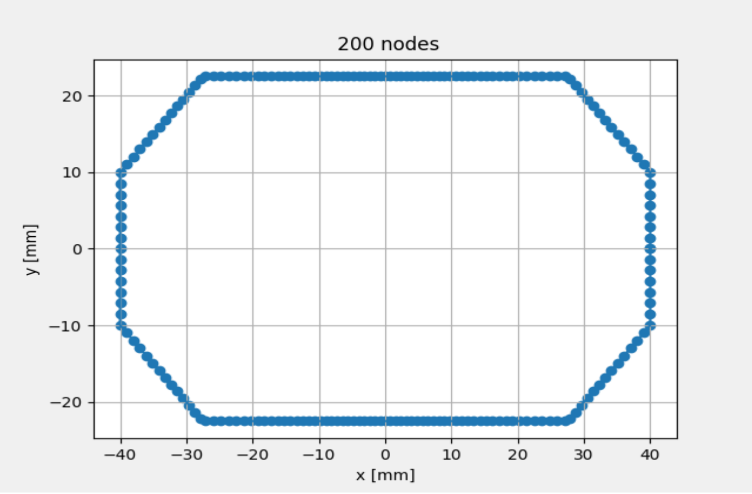
Boundary Conditions: $Z_0 H_\tau = -\frac{\kappa}{k} E_z, \qquad Z_0 H_z = \frac{\kappa}{k} E_\tau.$

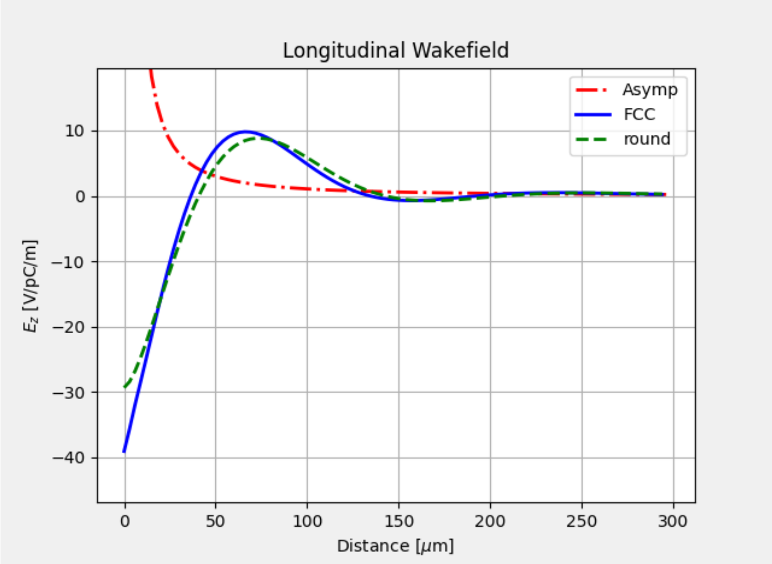
- This code is written in Fortran 77 and difficult to deploy. Therefore, we developed a python library that can run the program, prepare the correct format for Fortran 77 and postprocess the results.

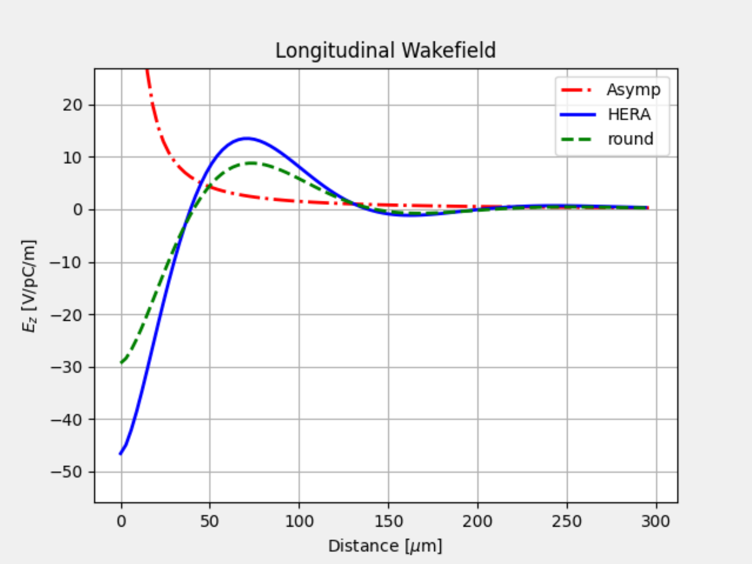
Results from Yokoya’s code

Running the Fortran Code by the Python package



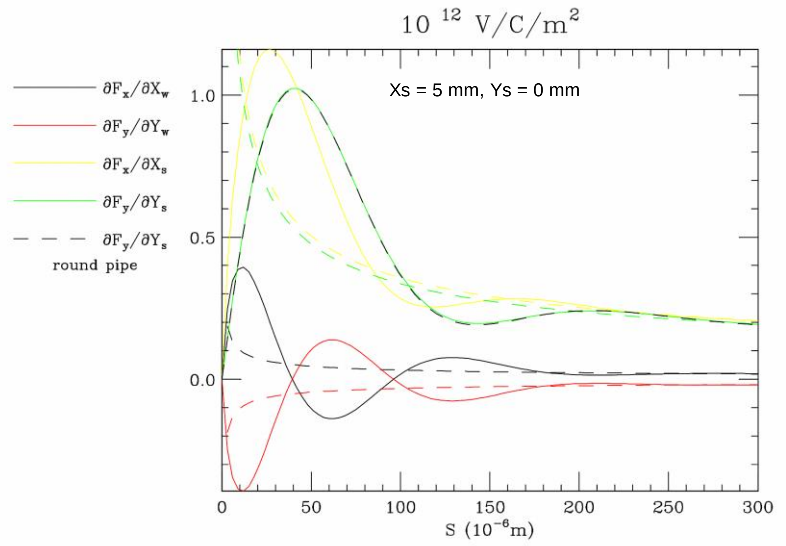


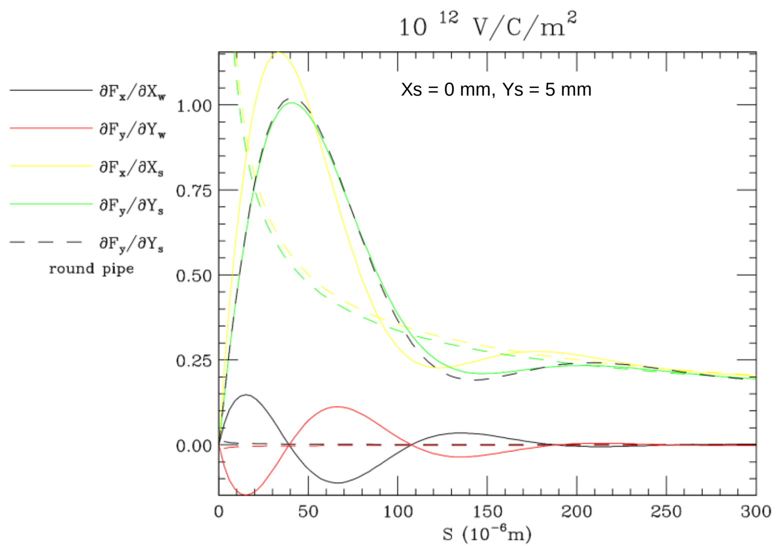


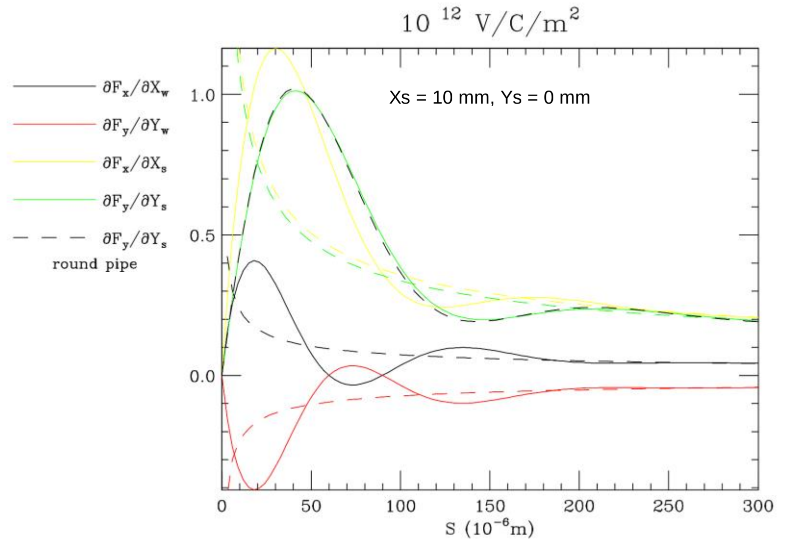


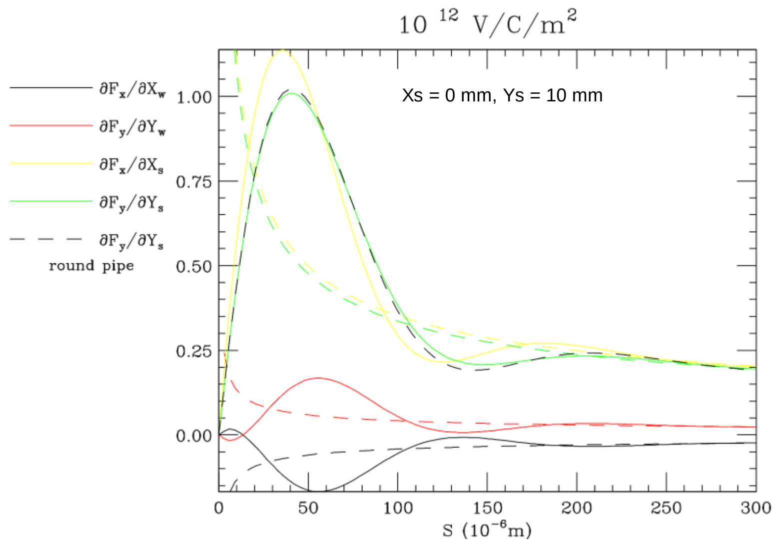
Results for off-axis Source Particle for FCC Geometry

Transverse wake from Post processing code





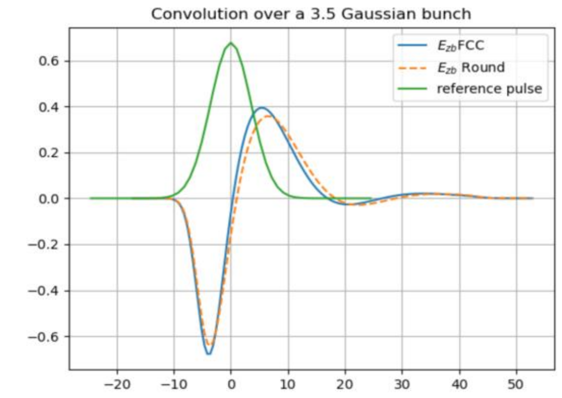


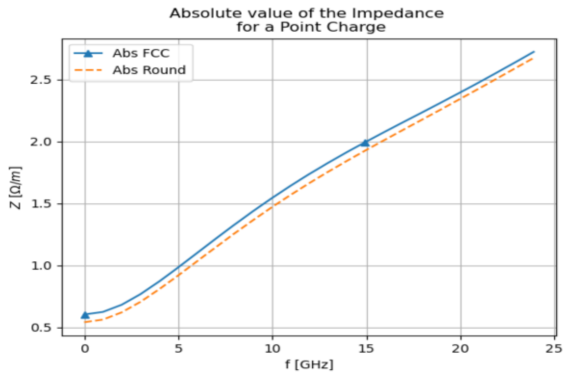


Impedance and bunch convolution based on Yokoya for FCC and Round Pipes

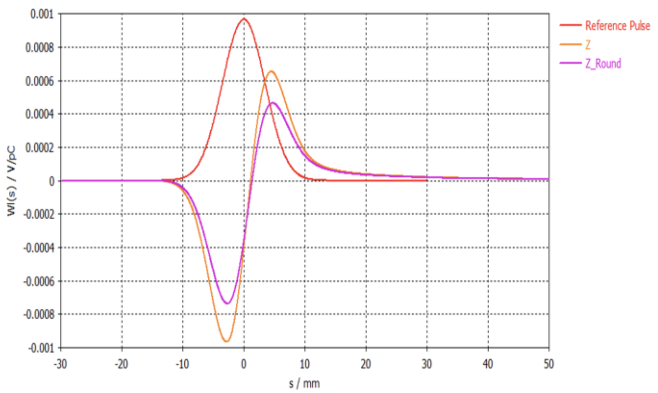
For a Gaussian beam ($\sigma = 3.5\ mm$)

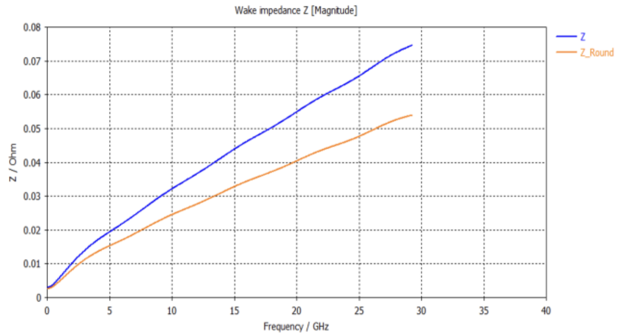
From post-processing code developed for Yokoya's code





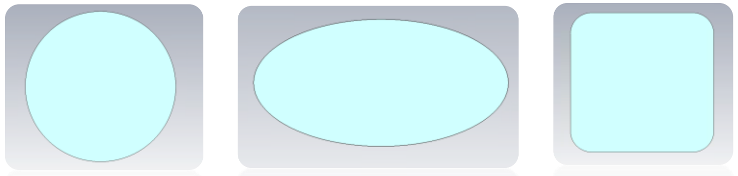
For Comparison results of the CST

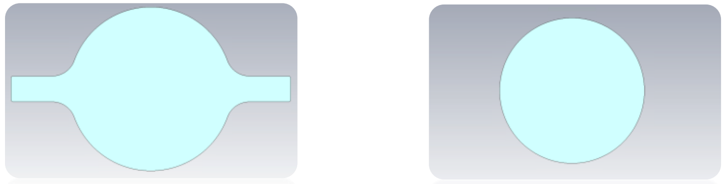




Is CST reliable for RW Impedance Calculation?

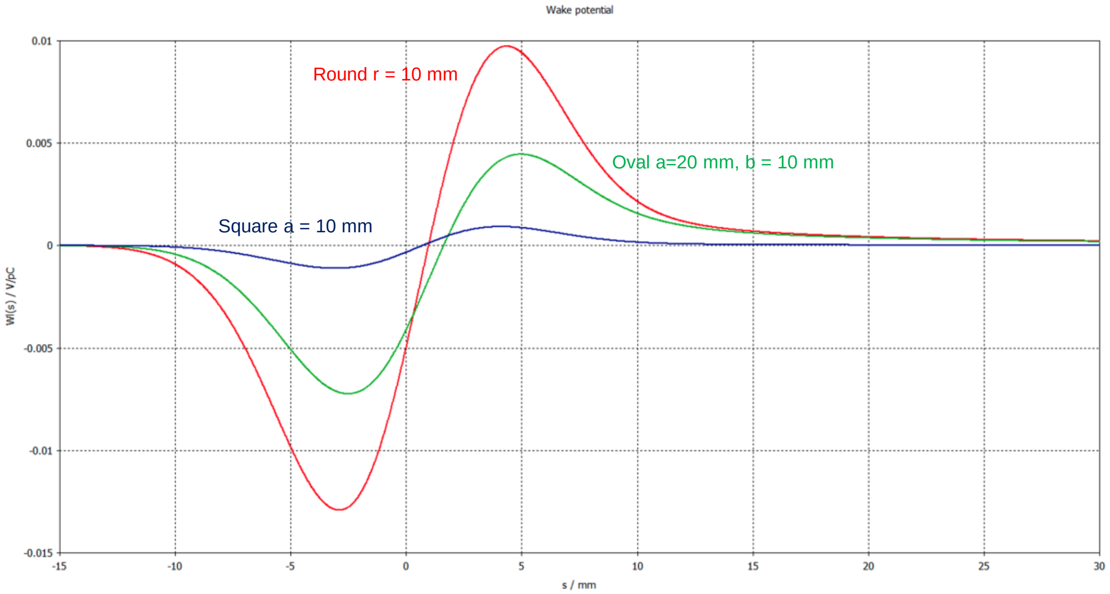
Compare between different Geometries

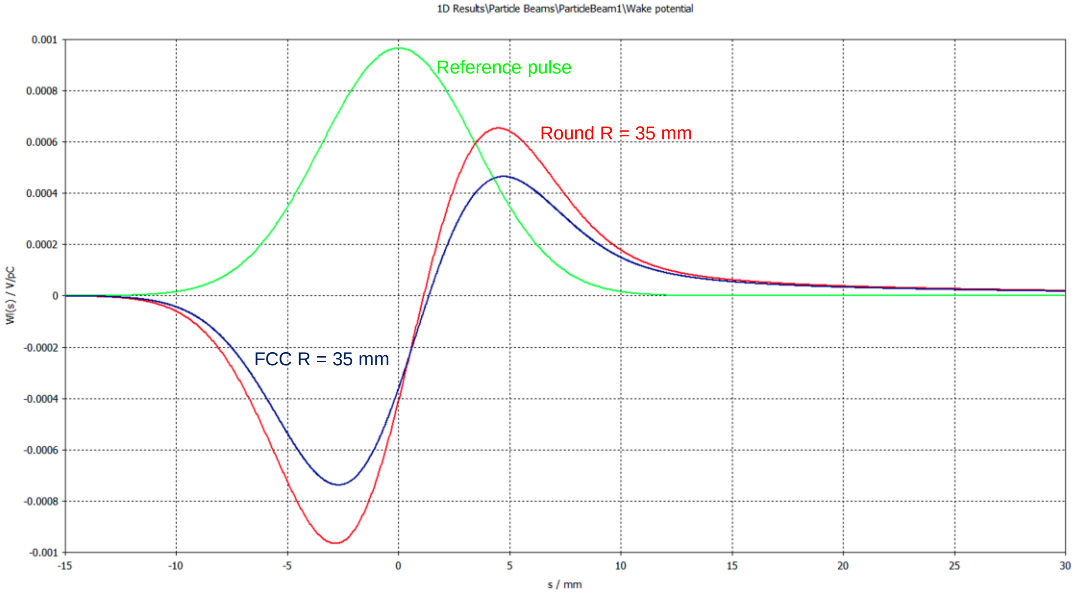




- Square, Round and Oval geometries (a = 20 mm and b =10 mm)
  For the same pipe length and simulation settings

- Round and FCC Geometries (Single-Layer)





How do BeamImpedance2D and IW2D codes work?

Finite Element Method

BeamImpedance2D (BI2D)

- A general 2D longitudinal and transvers impedance computation tool for arbitrary frequency and beam velocity.
- It is based on the finite element method (FEM) on an unstructured triangular mesh.

ImpedanceWake2D (IW2D)

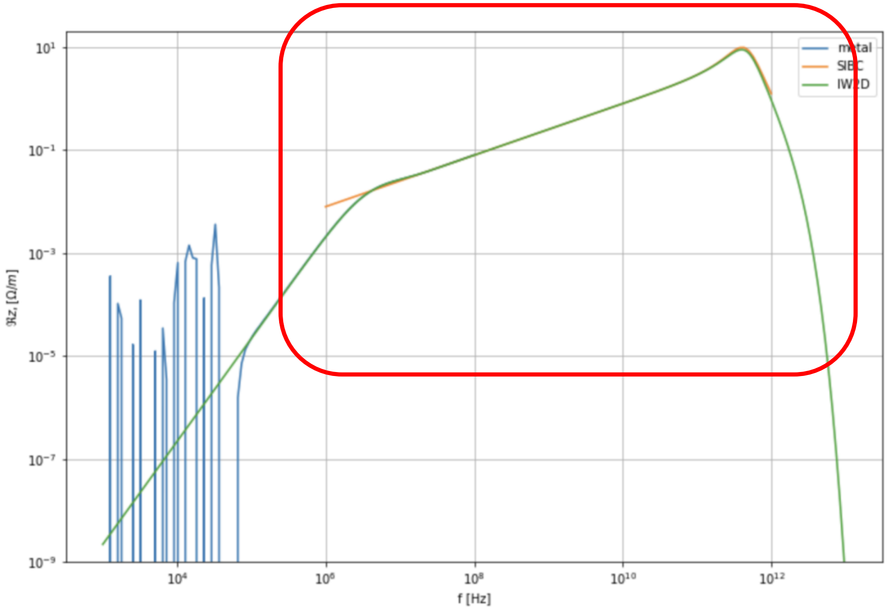
- The problem solved by the code is purely electromagnetic and very general obtaining the Green function for a travelling particle in a axisymmetric or flat structure.
- This code only supports flat and round pipes, and by using Yokoya's factor it can also calculate RW impedance for an elliptical pipe

Results from BeamImpedance2D and IW2D

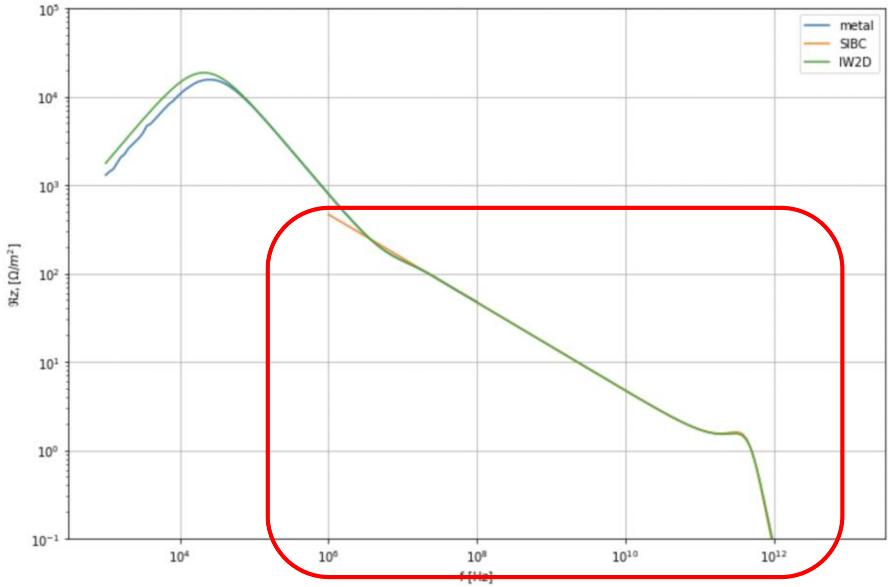
For a Single-Layer Steel pipe

Data from Sergey Matsievskiy from Cremlin project

Monopole Real part



Dipole Real Part



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Introduction to “VACI-Suite”

VACI-Suite for 2D and 3D Impedance calculation

VAcuum Chamber Impedance suite

By coincidence VACI also has a nice meaning in the world outside of the Physics:

A **Vital Absorbing Creative Interest**, or VACI, can help bring back the simple pleasure of living a life free of substances and unhelpful behaviors. When we get overly involved in any one activity, be it helpful or not so helpful, we cut a lot out of our lives that we used to enjoy.

In short:

VACI means finding a balance that can restore the fun and enjoyment in 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

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

2

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

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

3

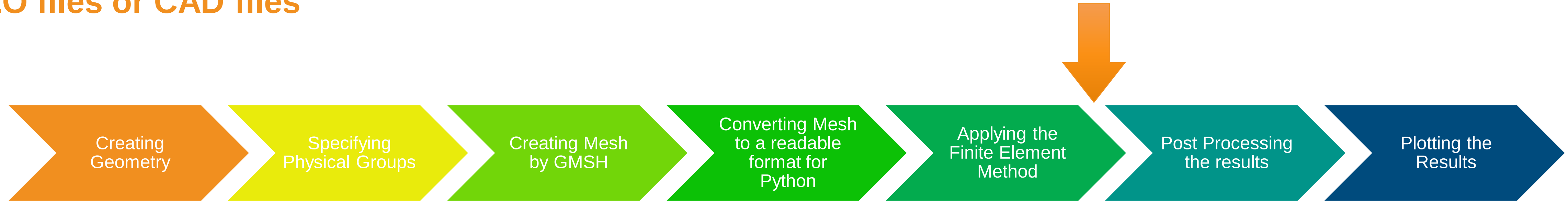
$$\nabla\times\underline{\nu}\nabla\times\underline{\vec{E}} - \omega^2\underline{\varepsilon}\,\underline{\vec{E}} = -i\omega\underline{\vec{J}}_s$$

$$\nabla\cdot\underline{\varepsilon}\underline{\vec{E}}_{\mathrm{curl}} = 0 \quad \text{and} \quad \nabla\times\underline{\vec{E}}_{\mathrm{div}} = 0$$

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

How does VACI work?

GEO files or CAD files




```
//+
SetFactory("OpenCASCADE");
Circle(1) = {0, 0, 0, 1, 0, 2*Pi};
//+
Curve Loop(1) = {1};
//+
Plane Surface(1) = {1};
//+
Physical Curve(2) = {1};
//+
Physical Surface(3) = {1};
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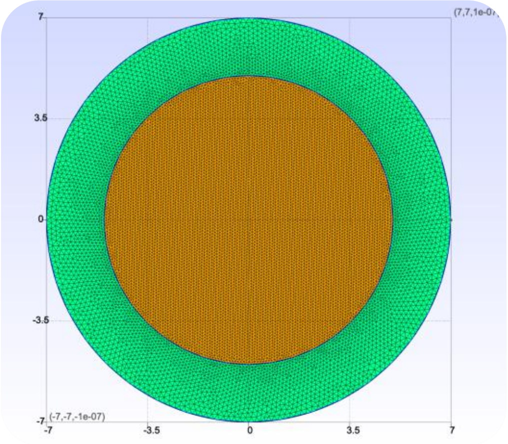

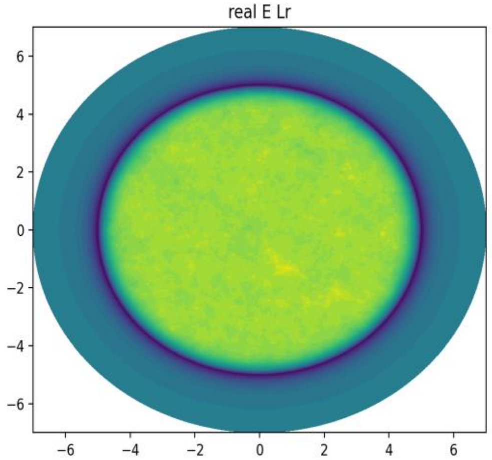

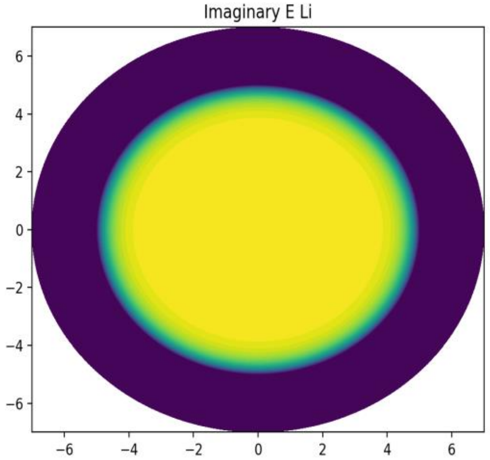

Comparison

Simulation codes

Yokoya's Code

- BEM solver
- Fast
- Single layer pipe
- General 2D Geo

BI2D and IW2D

- FEM for BI2D
- Fast
- Multi layer pipe
- General 2D Geometries for BI2D
- Only Round pipe for IW2K, and elliptical cross sections with Yokoya's factors

VACI-suite

- FEM ✓
- Fast (maybe) ✓
- Multi-layer ✓
- General Geometries ✓
- Parallel on CPU ✓
- Next Steps:
  - 3D FEM solver
  - CAD file as input
  - Parallel on GPU
  - Add BEM solver to 2D package
  - Add full ring impedance calculation
  - Integrate pyHEADTAIL (or similar particle tracker codes)
  - Maybe adding GUI to the program

Thank you for your Attention

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

Contact

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