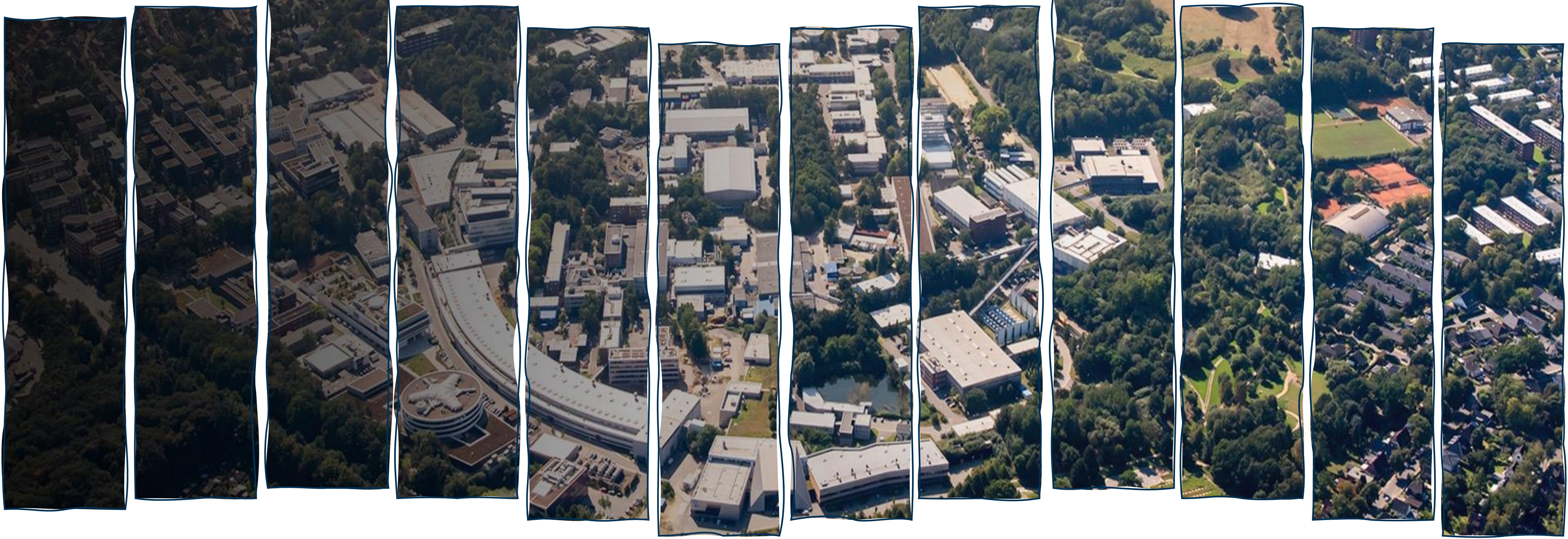


RW impedance and CBI

FCC Booster

Ali Rajabi
Rome, 13 November, 2023

HELMHOLTZ

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.

Table of content

Collective Effects and Instabilities

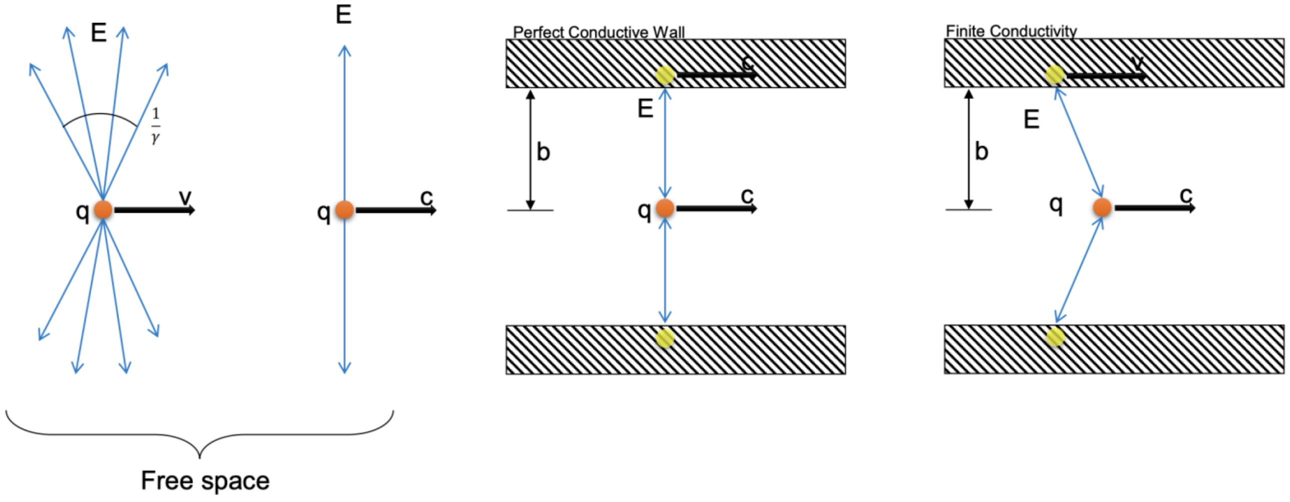
Collective Effects

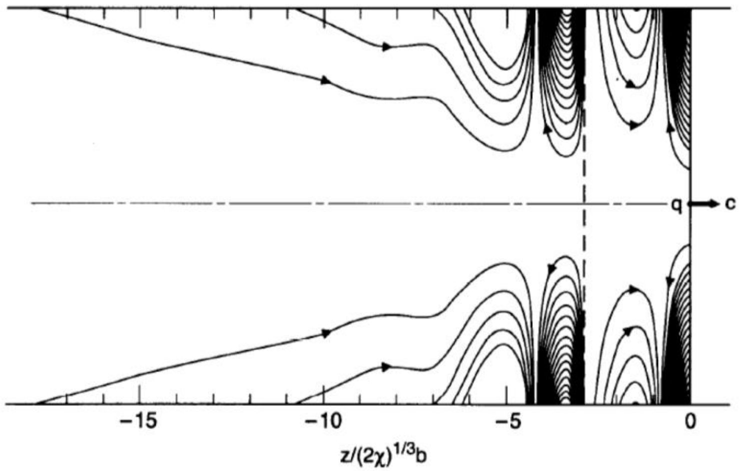
Introduction

What are collective effects?

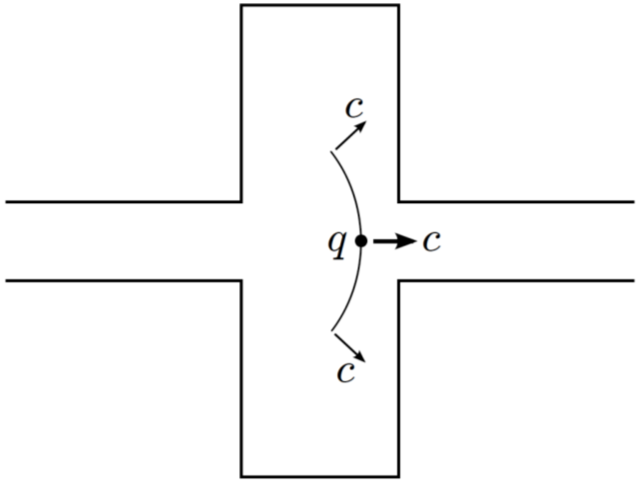
- Interactions between particles within a beam are generally known as collective effects

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





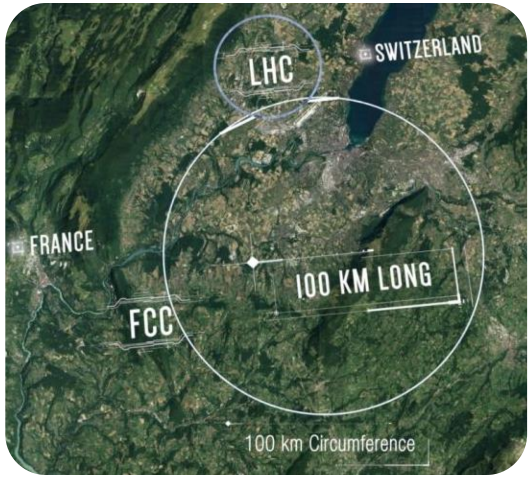
Wake fields following a point charge in a cylindrical beam pipe with resistive walls. (K. Bane)

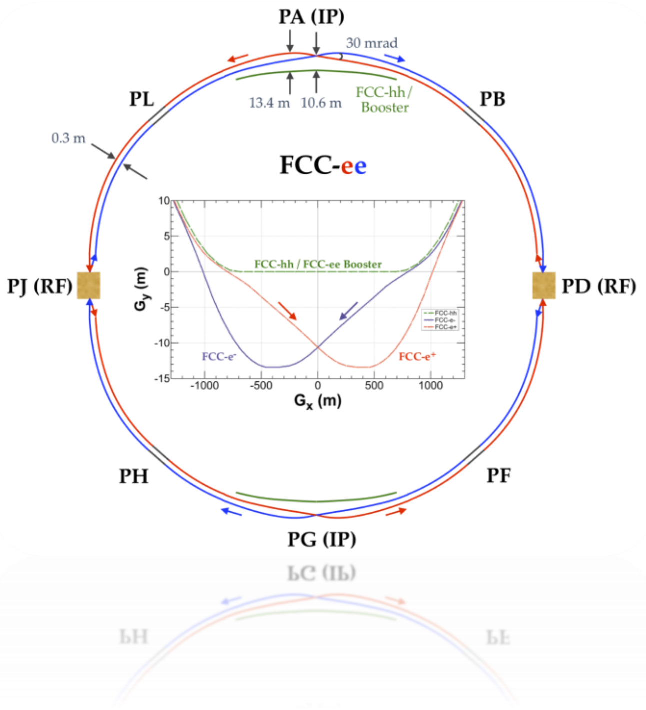


Source of Impedance in the Ring

FCC Rings (old parameters, CDR)

- Beam pipes (Resistive Wall Impedance, ~92 km)
- RF Cavities (No. 56 in a 4-cell array)
- RF Cavity Tapers (No. 14 double tapers)
- Synchrotron Radiation Absorbers
- Collimators (No. 20)
- BPMs (No. 4000)
- Bellows (No. 8000)





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

Boundary Condition

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

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

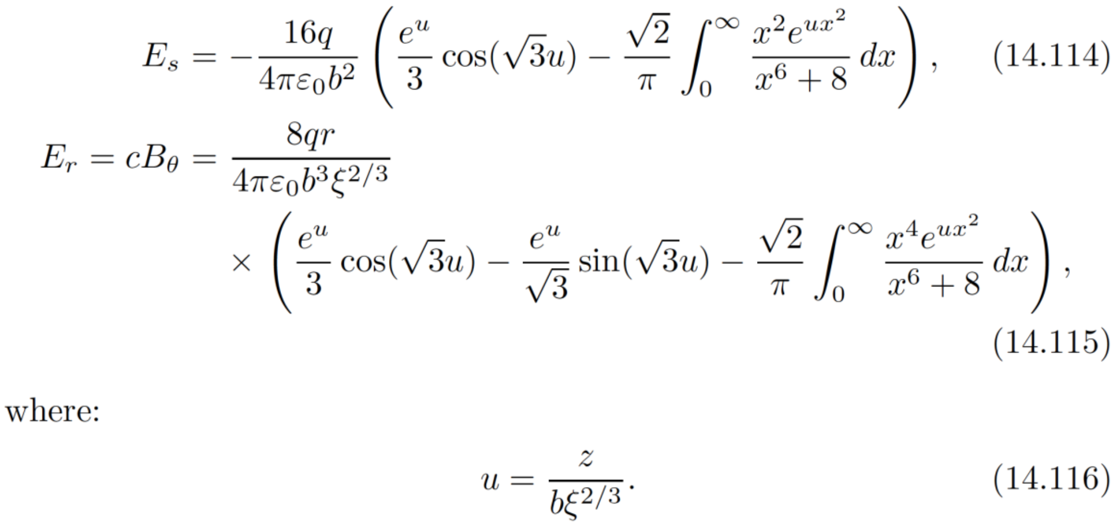
$\partial_t \Longrightarrow -i\omega$ Fourier Transform

$\partial_z \Longrightarrow -i\omega/v$ 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 wake-field

Simple Geometries

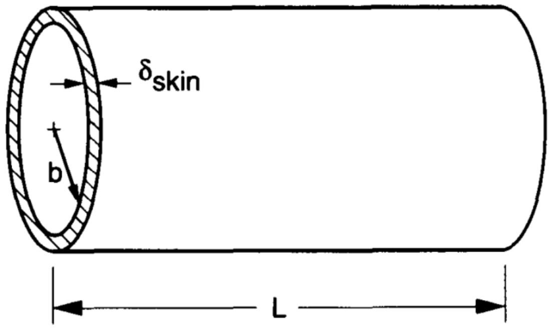


$$E_s = -\frac{16q}{4\pi\varepsilon_0 b^2}\left(\frac{e^u}{3}\cos(\sqrt{3}u) - \frac{\sqrt{2}}{\pi}\int_0^\infty \frac{x^2 e^{ux^2}}{x^6+8}\,dx\right), \qquad (14.114)$$

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

where:

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



FFT

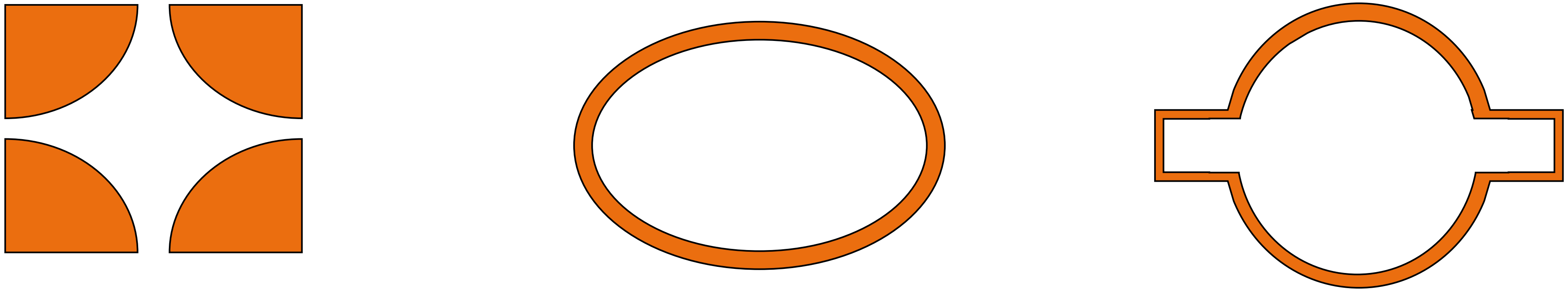
Wakefield

Impedance

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

Resistive wall wake-field

General Geometries



Simulation Codes

CST GDFIDL IW2D BeamImpedance2D

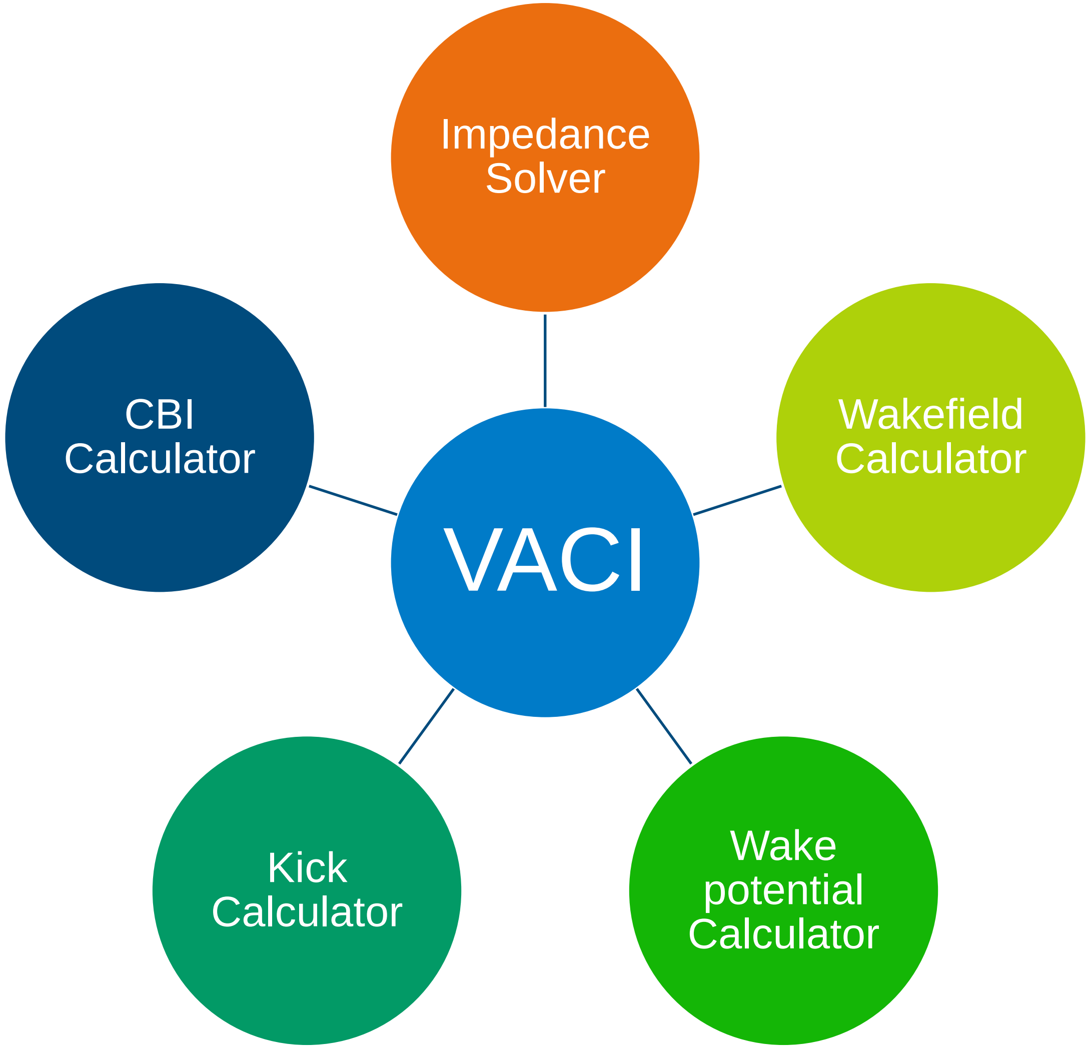
VACI

VACI Suite

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

VACI Suite

Modules



VACI

Impedance Solver

Wakefield Calculator

Wake potential Calculator

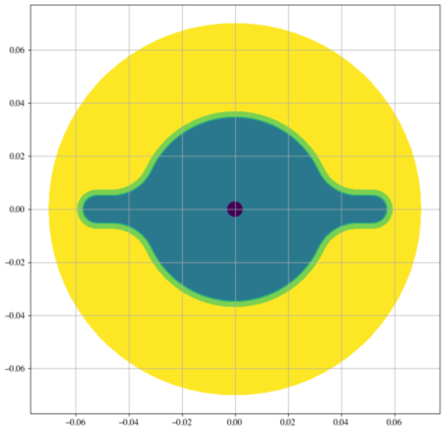
Kick Calculator

CBI Calculator

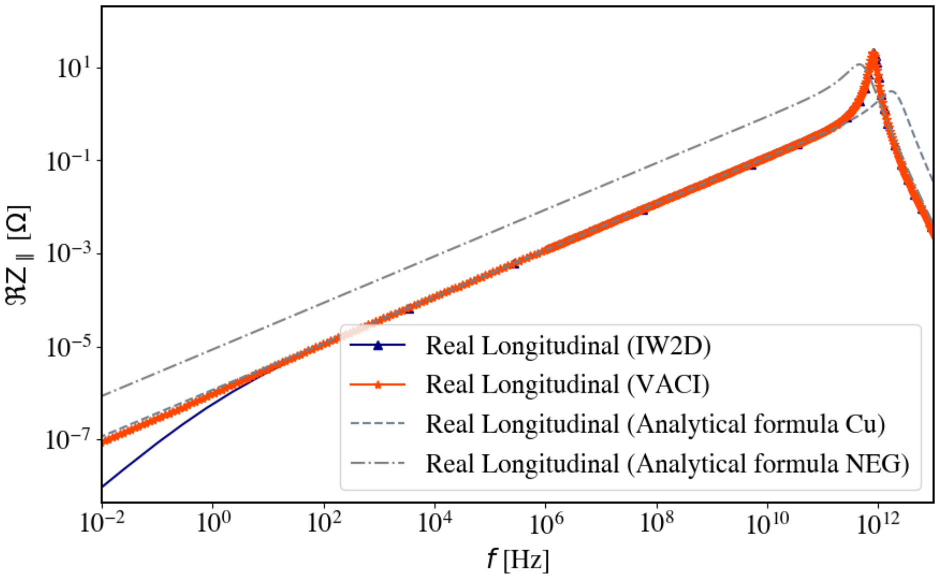
FCC main Ring

Monopolar Impedance

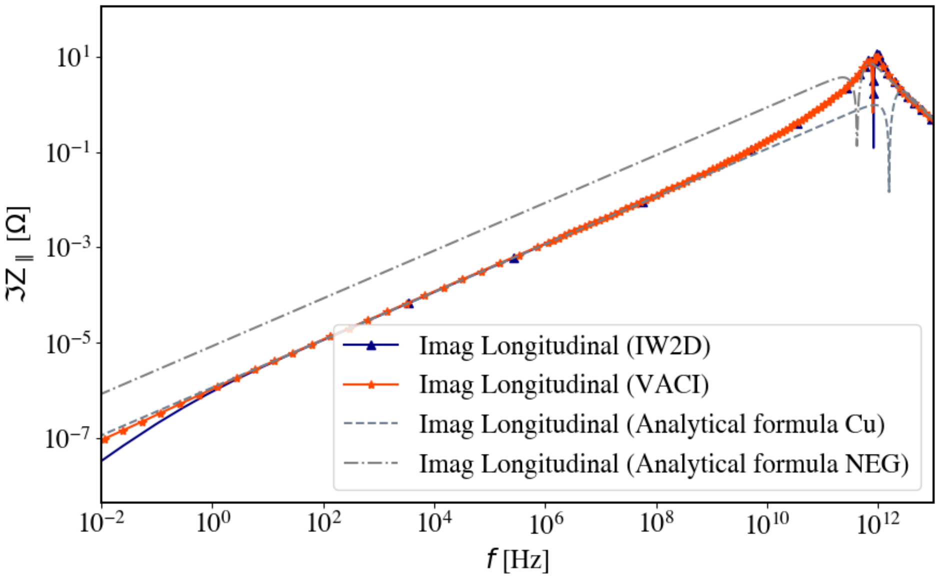
E -> 45.6 GeV
Pipe -> Cu (5.96e7 S/m)
NEG -> 1e6 (S/m)
R -> 35 mm



(a)

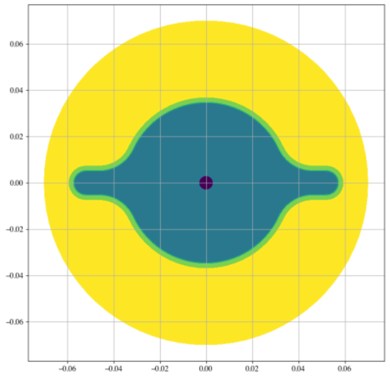


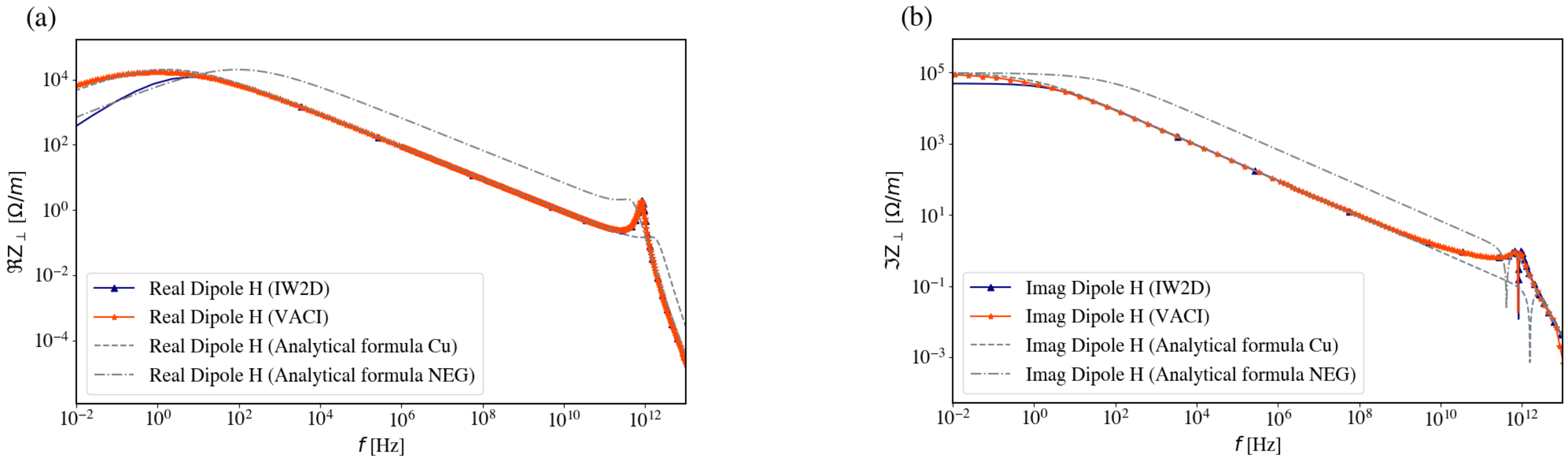
(b)

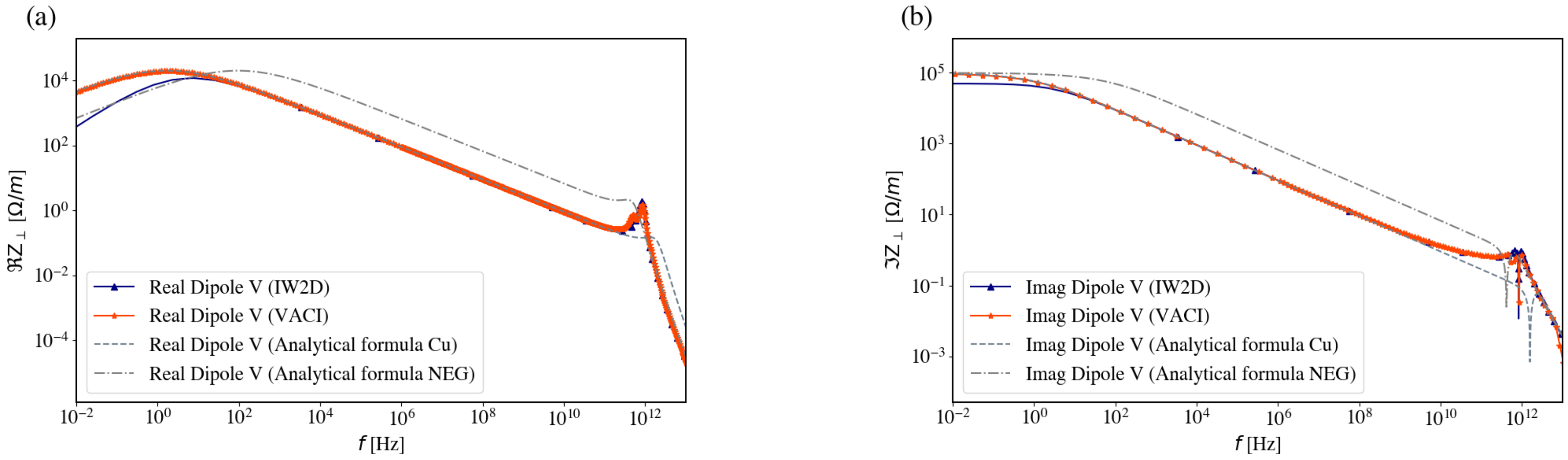


FCC main Ring

Dipolar Impedance

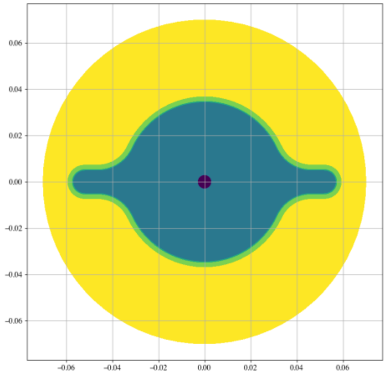




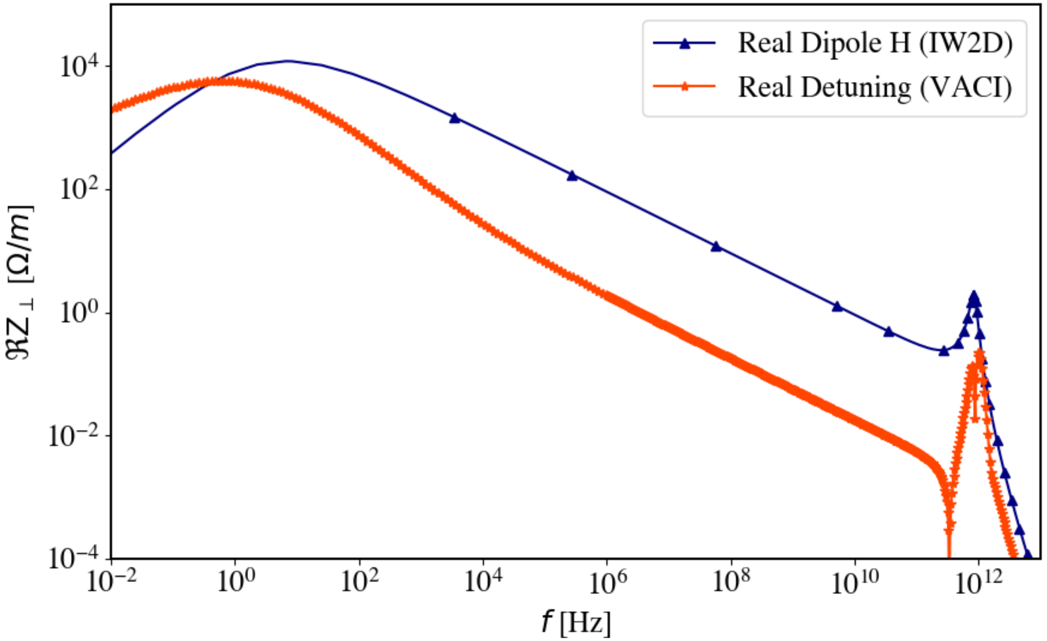


FCC main Ring

Detuning Impedance



$$W_x = x_s W_x^{dip} + x_w W_x^{det}$$



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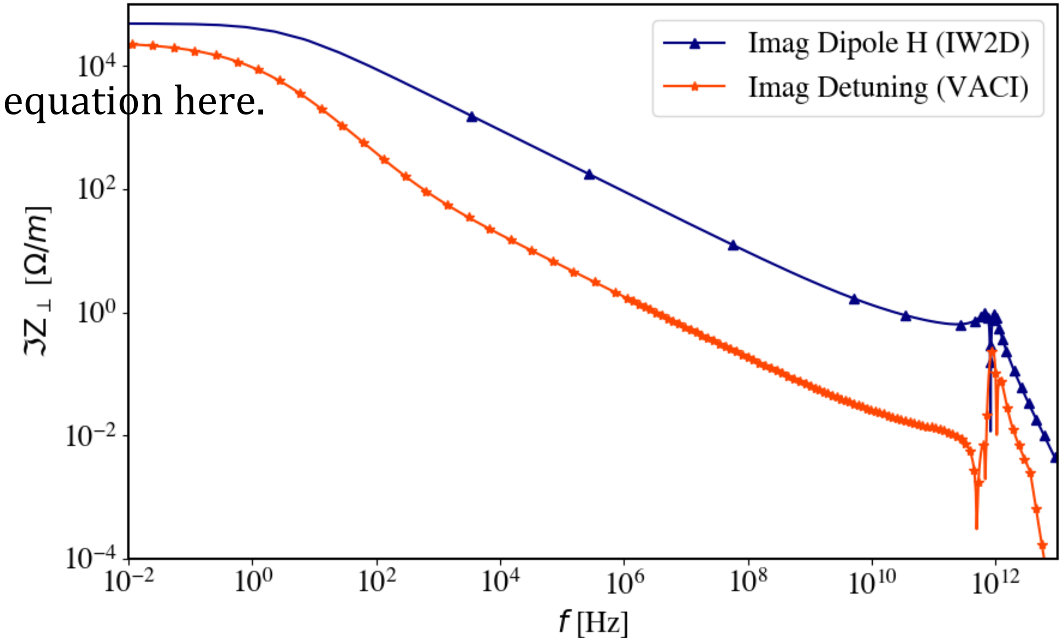
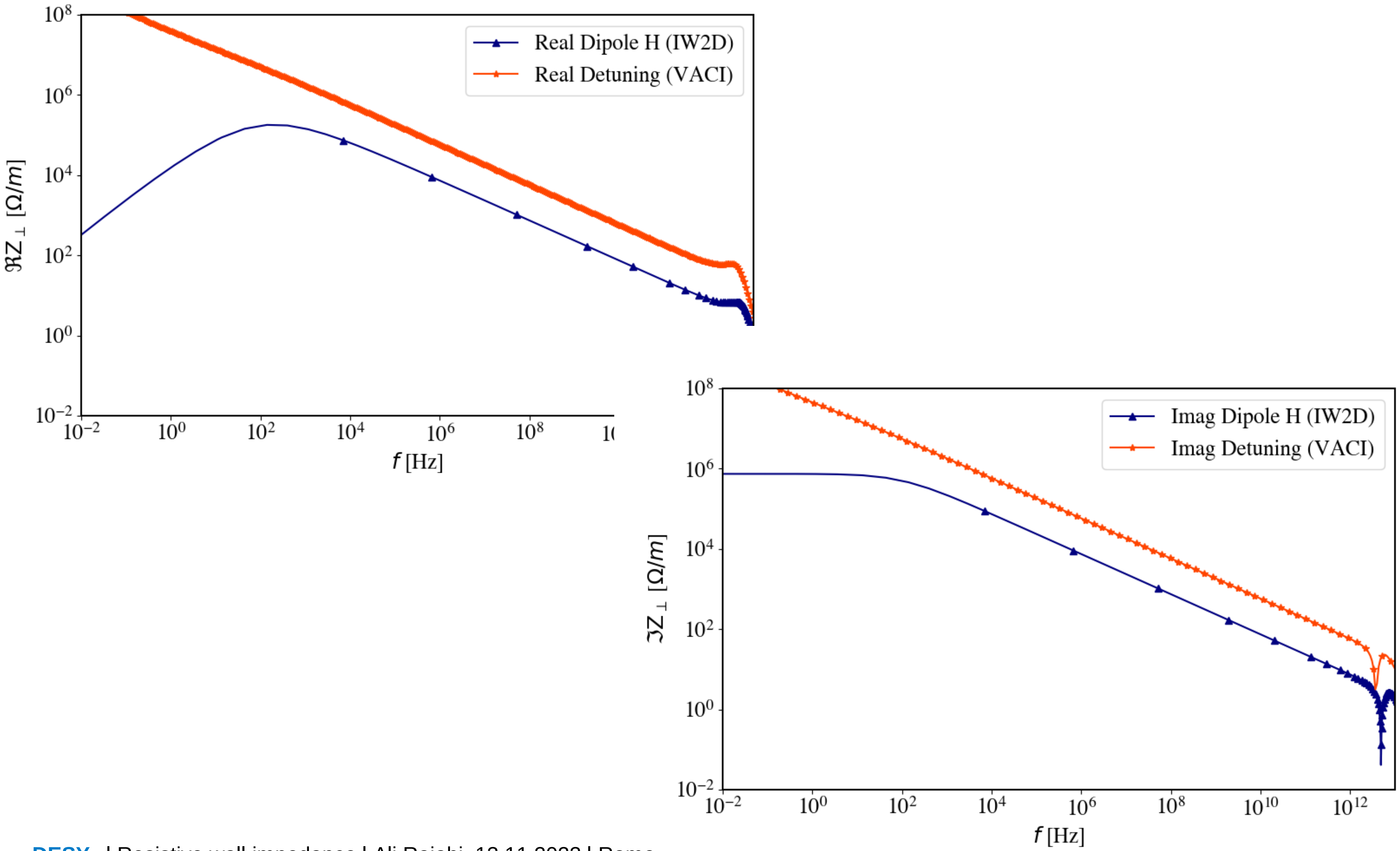
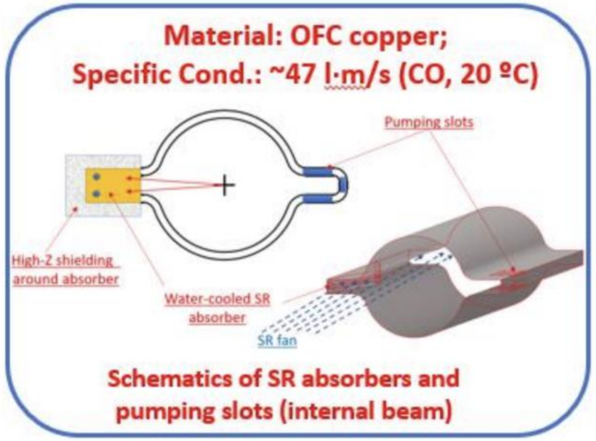


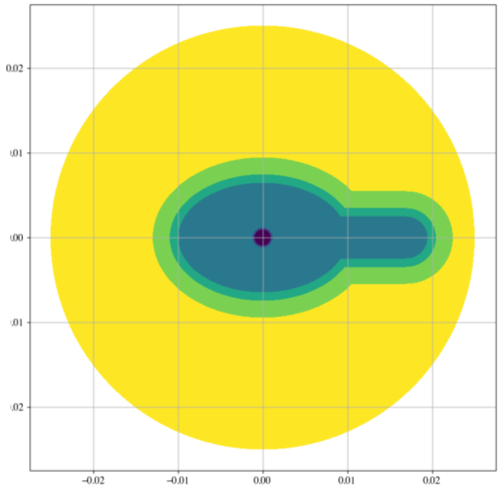
FCC main Ring

Considering absorbers





Presentation of R. Kersevan

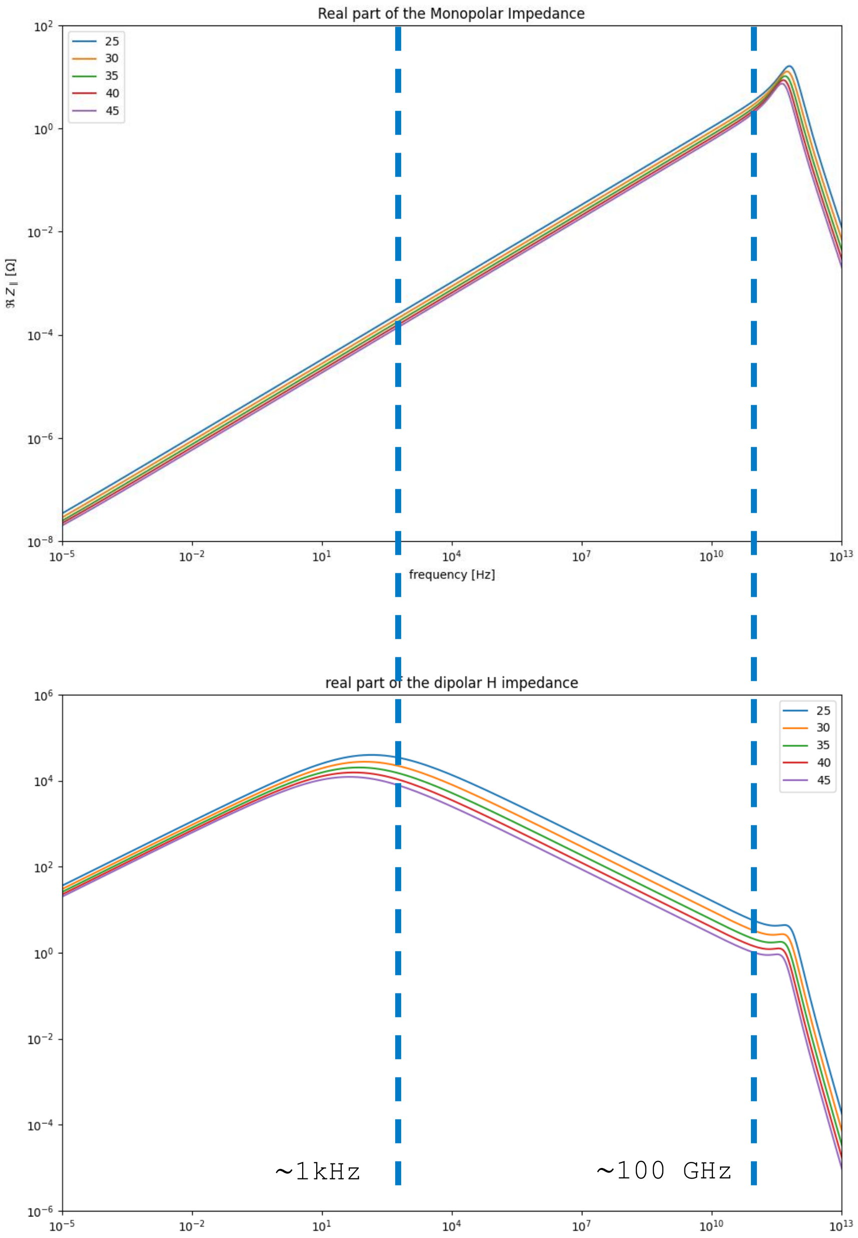


FCC Booster Ring

Impedance, Stainless Steel, different radius

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

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



Instabilities

Introduction

Classification of beam instabilities

- Single-Bunch instabilities
  - Longitudinal single bunch collective effects
    1. Short-range longitudinal wakefields and broadband impedance
    2. Potential well distortion
    3. Longitudinal microwave instability
    4. Measurements
    5. CSR microbunching instability
  - Transverse single bunch collective effects
    1. Short-range transverse wakefields and broadband impedance
    2. Head-tail modes (e.g. TMCI) and chromaticity
    3. Measurements
    4. Damping with feedback
  - Intrabeam (IBS) and Touschek scattering

- Multi-bunch instabilitie
  - Longitudinal Multibunch collective effects and cures
    1. Longitudinal coupled bunch instabilities
    2. Measurements
    3. Passive cures
    4. The Robinson Instability
    5. Harmonic RF systems
    6. Feedback systems
  - Transverse multibunch collective effects and cures
    1. Transverse coupled bunch instabilities
    2. Measurements
    3. Passive cures
    4. Feedback systems
  - Beam-Ion instabilities
  - Electron cloud instabilities

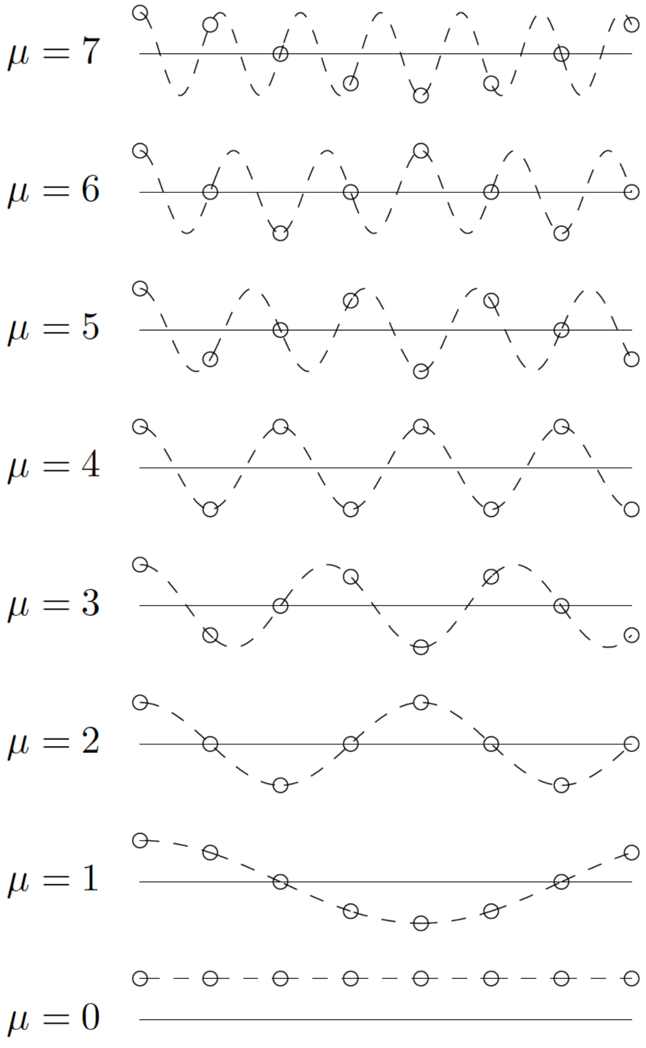
Collective Instabilities, John Byrd, USPAS, 2014

Transverse coupled bunch instabilities

Due to RW impedance

$$
\begin{cases}
\dfrac{d^2 x_n}{dt^2} + \omega_\beta^2 x_n = \dfrac{F_x}{\gamma_0 m N_b} \\[2em]
F_x = -\dfrac{(qN_b)^2}{C_0} \displaystyle\sum_{k=0}^{\infty} \sum_{n'=0}^{n_b-1} W_1(z)\, x_{n'}\left(t + \frac{z}{c}\right) \\[1em]
z = -\dfrac{(n' - n)}{n_b} C_0 - kC_0
\end{cases}
$$

$$\boxed{\omega_\beta^2 - \Omega_\mu^2 = -\frac{q^2 N_b c^2}{E_0 C_0} \sum_{k=-\infty}^{\infty} \sum_{n'=0}^{n_b-1} W_1(z) e^{2\pi i \mu (n'-n)/n_b} e^{-i\Omega_\mu z/c}}$$



Transverse coupled bunch instabilities

Due to RW impedance

$$\omega_\beta^2 - \Omega_\mu^2 = -\frac{q^2 N_b c^2}{E_0 C_0} \sum_{k=-\infty}^{\infty} \sum_{n'=0}^{n_b-1} W_1(z) e^{2\pi i \mu (n'-n)/n_b} e^{-i\Omega_\mu z/c}$$

$$\Omega_\mu - \omega_\beta = -i \frac{4\pi}{Z_0 c} \frac{n_b N_b r_0 \omega_0 c}{8\pi^2 \gamma_0 \nu_x} \sum_{p=-\infty}^{\infty} Z_1^\perp(\omega_\beta + (\mu - n_b p)\omega_0) \qquad n_b p = \frac{\Omega_\mu - \omega_p}{\omega_0} + \mu \qquad \nu_x = \omega_\beta / \omega_0$$

$$\mu - n_b p = -\mathrm{int}(\nu_x) - 1 \qquad \frac{1}{\tau} = \mathrm{Im}(\Omega_\mu) = \frac{n_b N_b r_0 c}{4\pi^2 \gamma_0 \nu_x b^3} \sqrt{\left(\frac{4\pi}{Z_0 c}\right) \frac{c C_0}{\sigma}} \frac{1}{\sqrt{1 - \mathrm{frac}(\nu_x)}}$$

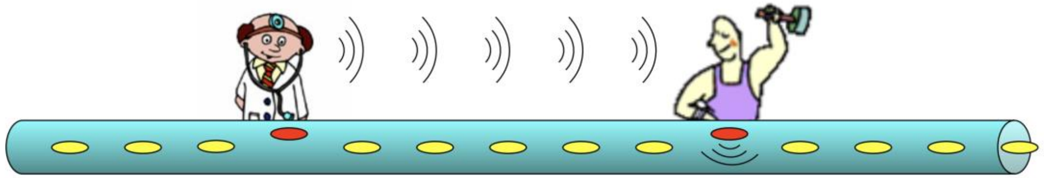
Transverse coupled bunch instabilities

Due to RW impedance

$$\frac{1}{\tau} = \mathrm{Im}(\Omega_\mu) = \frac{n_b N_b r_0 c}{4\pi^2 \gamma_0 \nu_x b^3} \sqrt{\left(\frac{4\pi}{Z_0 c}\right) \frac{c C_0}{\sigma}} \frac{1}{\sqrt{1 - \mathrm{frac}(\nu_x)}}$$

- Growth rate for transverse resistive wall CBI depends:
  - Strongly on the beam pipe radius ∝ $1/b^3$
  - Weakly on the conductivity ∝ $\sqrt{1/\sigma}$

- Therefore, replacing the booster's beam pipe from copper (or stainless steel with a copper coating) to stainless steel, wherein we need to augment the beam pipe radius to offset the effects of TMCI, would be advantageous for CBI



Courtesy: Marco Lonza

Outlooks

Beam Dynamics with XSuite

- Impedance budget of booster ring (with Mauro Migliorati and Adnan Ghribi)
- TMCI for the main and booster rings with Xsuite (One turn Matrix)
- Distributed Wakefields and physical apertures with local wakefields (maybe, full Ring)
- Intrabeam scattering
- Multibunch tracking
- Feedback system
- Ramp-up

Thank you

Contact

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