Vacuum for Particle Accelerators

Impedance tutorials:

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Many thanks for their help and support to

David Amorim, Nicolo Biancacci and Francesco Giordano (CERN, ImpedanceWake2D)

Monika Balk (CST AG) for kindly providing the licenses for the course

Jean-Jacques Gratier (Computer Controls) for kindly loaning us a network analyzer
Programme

• Short recap on impedance
  -> main key parameters:
    - power loss and loss factor
    - effective impedances and kick factor
    - resonant modes

• Impact of material → ImpedanceWake2D
  (code developed at CERN by Nicolas Mounet et al)

• Impact of geometry → CST simulations
  (3D commercial code: www.cst.com )

• Main messages
Impedance?

• When a beam of particles traverses a device which
  • is not smooth
  • or is not a perfect conductor,
  it will produce electromagnetic RF fields that will perturb the following particles
  → wakefields (in time domain) or impedance (in frequency domain).

• Example of wakefield perturbation caused by an obstacle in a beam pipe:

  In a smooth beam pipe

  ![Image of a smooth beam pipe]

  In a beam pipe with a sharp obstacle → resonant RF mode

  ![Image of a beam pipe with a sharp obstacle]

Impact of impedance?
1) Energy is lost by the beam
2) Resonant kicks to following particles

→ Are these impedance perturbations an issue?
Impact of impedance?

1) Energy is lost by the beam → dissipated in surrounding chambers → beam induced heating
2) Resonant kicks to following particles → instabilities → beam loss and blow-up

- More beam intensity → more perturbations → more damage and beam quality issues
- Impedance is a critical limit to increase the performance of most large accelerators
- Requires strict continuous follow-up and support → mandate of the impedance working group at CERN
→ Solves Maxwell’s equation in frequency domain for a multilayer vacuum chamber made of arbitrary materials
→ Ref: PhD thesis Nicolas Mounet (EPFL 2012)

→ Field matching at all material boundaries
→ Quite a lot of maths with clever tricks to gain computing time, out of the scope of this tutorial
→ Outputs the impedance contributions as a function of frequency
CST simulations

• 3D commercial code that allows:
  • Simulating a beam inside a device (wakefield solver) ➔ time domain simulation
  • Finding resonant modes of a structure without beam (eigenmode solver) ➔ frequency domain simulation

1st example: open and run the wakefield file 0_cavity_test.cst

Observe:
- the exciting bunch
- The resonant modes in the 2D/3D Results
- The resonant modes in the 1D Results wake impedance
Main impedance contributions to watch out for:

→ For all contributions, need to check the resonant modes and the “broadband” impedance part

→ First major message: impedance of a device is not a number, it is a complex function of frequency in all 3 planes → many contributions to check and optimize
Practical description of impedance (see Rainer Wanzenberg’s talk)

• Discrete resonant modes:
  • Shunt impedance $R$
  • Quality factor $Q$
  • Resonant frequency $f$

• Integrated impedance: several conventions
  • Some use loss/kick factor to describe the impedance
    → advantage: direct link to energy loss and kick felt by a test particle
  • Some use effective impedances
    → advantage: contains both real and imaginary components for instability assessment with Sacherer’s formalism
practical description: see Frank Zimmermann USPAS 2015

Effective impedance

\[
\left( \frac{Z_0^{\parallel}}{n} \right)_{\text{eff}} \equiv \omega_0 \left( \frac{Z_0^{\parallel}}{\omega} \right)_{\text{eff}} = \omega_0 \frac{\int_{-\infty}^{\infty} \frac{Z_0^{\parallel}(\omega')}{\omega'} |\tilde{\rho}(\omega')|^2 d\omega'}{\int_{-\infty}^{\infty} |\tilde{\rho}(\omega')|^2 d\omega'}
\]

Loss/kick factors

\[
k_{\parallel} = \frac{1}{\pi} \int_0^\infty \text{Re} \left[ Z_0^{\parallel}(\omega) \right] |\tilde{\rho}(\omega)|^2 d\omega
\]

\[
k_{\perp} = -\frac{1}{\pi} \int_0^\infty \text{Im} \left[ Z_1^{\perp}(\omega) \right] |\tilde{\rho}(\omega)|^2 d\omega
\]

→ Different conventions depending on the machine, the lab (or the group)
→ We will use effective impedances in this tutorial
Prewarning

Note: this is not a tutorial to get you impedance experts, but more to see how impedance experts deal with your inputs, needs and constraints.

- As little code writing as we could
- Many examples ready to run to see correlations and parameter dependence.
- Try to get main messages through, the main ones:

Impedance is generally minimized when the surrounding beam pipe is:
  - far from the beam
  - smooth
  - as good conducting as possible in the frequency range of interest
  - and cavities (large or small) are avoided or shielded
Prewarning: impact of bunch length

- Impedance can be strongly dependent on excitation frequency
- Change of bunch length directly affects the range of frequencies excited by the bunch
- What is not causing trouble in one machine may be a very large issue in another machine

![Charge distribution amplitude spectrum](image)

Smaller bunch length $\rightarrow$ larger frequency spectrum excited
Programme

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• Main messages
Impact of beam pipe

1) Length
2) Radius
3) Conductivity
4) Thickness
5) Bunch length
6) Coatings
Understanding the impact of material thickness:

Case of an 18 mm diameter pipe made of 1 mm thick copper, surrounded by vacuum

Question: how much length of such a copper pipe would be allowed in LHC assuming the current allowed limit is 0.2 MOhm/m at injection?
Impact of material length

$\rightarrow Z_t^{\text{eff}} \propto L$

$\rightarrow P_{\text{loss}} \propto L$
Question: what is the effective transverse impedance and power loss for 1 m of beam pipes with radius of
- 1 mm
- 5 mm
- 10 mm
- 30 mm

How do power loss and effective transverse impedance depend on radius?
How much length of LHC can you install if one assumes that the limit is 0.2 MOhm/m?
Impact of beam pipe radius

\[ Z_t \propto \frac{L}{b^3} \]

\[ P_{\text{loss}} \propto \frac{L}{b} \]
Impact of beam pipe radius

\[ Z_t \propto \frac{L}{b^3} \]
\[ P_{\text{loss}} \propto \frac{L}{b} \]
Impact of material conductivity

Question: what is the effective transverse impedance for 1 m of beam pipes with conductivity of
- 1e5 S/m (similar to graphite)
- 1e6 S/m (similar to stainless steel)
- 1e7 S/m
- 1e8 S/m (similar to copper)
- 1e10 S/m (similar to 20 K cold copper)

How much length of LHC can you install if one assumes that the limit is 0.2 MOhm/m?
Impact of material conductivity

→ $Z_t \propto \sqrt{\rho} \cdot \frac{L}{b^3}$

→ $P_{loss} \propto \sqrt{\rho} \cdot \frac{L}{b}$
Impact of material conductivity

$\rightarrow Z_t \propto \sqrt{\rho} \cdot \frac{L}{b^3}$

$\rightarrow P_{\text{loss}} \propto \sqrt{\rho} \cdot \frac{L}{b}$
Question: what is the effective transverse impedance for 1 m of copper beam pipe with thickness of
- 10 cm
- 1 cm
- 1 mm
- 0.1 mm
- 0.001 mm
- 0.0001 mm
Can we understand this behaviour?
Impact of beam pipe thickness

→ Beyond a certain thickness related to the skin depth, changing the thickness does not have an impact on impedance

Skin depth is larger than the thickness
Fields escape → image currents have to stay closer to the beam → larger effective impedance

→ Not trivial, needs to compute solution every time
Impact of beam pipe thickness

- Change of sign of the difference with thick when thickness decreases
- Always smaller when thickness decreases
- Simple formula do not apply anymore
- Strong impact of bunch length...
Impact of bunch length

Question: what is the effective transverse impedance for 1 m of copper beam pipe with thickness interacting with an rms bunch length of:
- 1 mm
- 1 cm
- 10 cm
- 100 cm
Can we understand this behaviour?
Impact of bunch length

- The bunch length does not change the impedance itself, but changes the frequency range of interest.
- Beware: bunch length also comes in the computation of instabilities

Perturbation of transverse tune

Due to impedance

$$\Delta \omega_{m,q}^{x,y} = \left( |m| + 1 \right)^{-1} \frac{j e \beta I_b}{2 m_0 \gamma Q_{x0,y0} Q_0 L} \left( Z_{x,y}^{\text{eff}} \right)_{m,q},$$

with

$$\left( Z_{x,y}^{\text{eff}} \right)_{m,q} = \sum_{k=-\infty}^{k=+\infty} Z_{x,y} \left( \omega_k^{x,y} \right) h_{m,q} \left( \omega_k^{x,y} - \omega_{x,y} \right),$$

→ In the end: beneficial impact of larger bunch length on instabilities
→ What works in one machine may not work in another!

Impact of bunch length

→ Ploss is proportional to $\sigma^{-3/2}$

→ Machines with very small bunch length have more heating from resistive wall.
Impact of beam screen

1) Length
2) Radius
3) Conductivity
4) Thickness
5) Bunch length
6) Coating
   - Copper on stainless steel (good on bad conductor)
   - NEG on copper (bad on good conductor)
Case of copper coating on graphite

Question: what is the effective transverse impedance for 1 m of stainless steel beam pipe with a copper coating of thickness:
- 10 nm
- 100 nm
- 1 micron
- 10 micron
- 100 micron

Can we understand this behaviour? How much copper coating thickness is needed to recover the copper case?
Copper coating on stainless steel

When skin depth is larger than the coating thickness, fields penetrate inside the stainless steel.

Transition between “copper alone” line and “stainless steel” line depends on coating thickness.

Very important to tune this transition with the bunch length to integrate over frequencies over which mainly copper matters, and not what is behind.
Copper coating on stainless steel

→ 10 microns of copper coating are enough to mimic a bulk copper for the LHC type beam (~10 cm bunch length)
Copper coating on stainless steel for ~1 mm bunch length

→ Integrate to higher frequencies for which the skin depth is smaller
→ 1 microns of copper coating are enough to mimic a bulk copper for the LHC type beam (~10 cm bunch length)
→ Large factors can be gained! Coatings are very important to push performance!
Impact of beam pipe

1) Length
2) Radius
3) Conductivity
4) Thickness
5) Bunch length
6) Coating
   - Copper on stainless steel (good on bad conductor)
   - NEG, carbon and TiN on copper (bad on good conductor)
Question: what is the effective transverse impedance for 1 m of stainless steel beam pipe with a copper coating of thickness:
- 100 nm
- 1 micron
- 10 micron
- 100 micron

Can we understand this behaviour? How much NEG coating thickness is needed to minimize the impact of the NEG?
Case of NEG coating on copper

→ Same as before: slow transition from Copper alone to NEG alone
→ Impact of decrease of bunch length?
Case of NEG coating on copper

→ Same as before: slow transition from Copper alone to NEG alone
→ Impact of decrease of bunch length?
Case of NEG coating on copper

→ Effective impedance saturates to copper for 100 nm NEG coating
→ Power loss saturates to copper for 1 micron NEG coating
Case of carbon and TiN coating on copper

Try with carbon coating and TiN: conductivity = $10^4$ S/m and $5 \times 10^6$ S/m

Question: what is the effective transverse impedance for 1 m of copper beam pipe with a carbon/TiN coating of thickness:
- 100 nm
- 1 micron
- 10 micron

Conclusion?
Carbon coating on copper

→ Large impact on effective imaginary impedance
→ Small impact on real impedance   →  almost no power loss
Carbon coating on copper

- Large impact on effective imaginary impedance as the fields are dephased by the thin layer
- Small impact on real impedance → almost no power loss in the coating
- How does this change with decreasing bunch length?
TiN coating on copper

Transverse impedance vs frequency (imaginary)

Longitudinal impedance vs frequency (real)
TiN coating on copper

→ also impact on effective imaginary impedance
→ larger impact on real impedance as more currents are contained in the TiN layer for the same frequency
Case of carbon and TiN coating on copper

Important conclusion:
- If coating thickness is low enough, limited impact and independent of conductivity
- Better conductivity is not always better
- Very strong impact of bunch length
Just for fun...

• Replace copper by dielectric (high resistivity $4 \times 10^{12}$ Ohm.m and epsilon’=5).
Try your own beam and vacuum chamber parameters

- Who wins for power loss?
Materials: what have we learnt?
Assignment #1

Find out a trade-off for power loss, longitudinal impedance, transverse impedance and SEY of the current design of the FCC-ee beam screen:

• Carbon coating
• NEG coating
• Laser treatment
• TiN coating
• No coating
• Other ideas?
• High temperature superconductor

• Substrate:
  • Stainless steel
  • Copper
  • Other ideas

References: R. Kersevan FCC week 2017 Berlin
https://indico.cern.ch/event/556692/contributions/2487640/attachments/1468449/2271161/FCC-Berlin-HS.pptx
E. Belli et al, FCC week 2017 Berlin
https://indico.cern.ch/event/556692/contributions/2590409/attachments/1468391/2271528/FCCWeek2017_Belli_CollectiveEffectsFCCee.pptx
Simulations

• Bellows
• Cavities
  • Shielding with fingers and ferrites
Perfect conducting tube: file: 1_PECtube.cst

- Question: what impedance do we expect?
- How do you interpret what you see?
- Look at the 3D fields to see the beam fields and the wakefields
Copper conducting tube:
file: 2_coppertube.cst

• Question: what is the difference?
• do we recover what we computed with the analytical tool?
Comparing perfect conducting tubes

→ conclusion: beware of numerical noise!
→ When impedance is already well optimized, relative error bar increases
• Question: what are the major differences with the pipe without convolutions in the impedance spectra?
• Can you find the dependence of the impedance properties (low frequency contributions and mode frequencies) with the convolution depth, convolution length, pipe radius and number of convolutions?
Formula for bellows

Theory: K. Ng

Longitudinal effective impedance

\[
\frac{Z_{\|}}{n} = j \frac{Z_0 \beta \ell}{2 \pi R} \ln \frac{b + \Delta}{b}.
\]
Proportional to \(l^* \Delta/b\) if \(\Delta \ll b\)

Transverse effective impedance

\[
Z_\perp = j \frac{Z_0 \ell}{2 \pi} \left[ \frac{1}{b^2} - \frac{1}{(b + \Delta)^2} \right].
\]
Proportional to \(l^* \Delta/b^3\) if \(\Delta \ll b\)

→ Linear impact of convolution depth and overall bellow length
→ Strong impact of the radius
Bellows contributions

Let’s assume:
- $n_{conv}=3$
- $inner\_radius=20\ mm$
- $conv\_length=8\ mm$
- $conv\_depth=8\ mm$

How many such bellows could we install in LHC if the full LHC budget at injection was allocated to bellows (2 MOhm/m in the transverse plane and $Z/n=0.1\ Ohm$ in the longitudinal plane)?

To how much length of 20 K cold copper beam pipe does 1 bellow correspond to for the transverse plane?

→ conclusion: please avoid bellows whenever possible or shield them!
Cavity:
file: 5_cavite_wake.cst

→ Resonant modes resonate for ever in the structure if the structure is a good conductor
→ Eigenmode simulations are better suited to quantify resonant modes
Cavity with eigenmode solver
file 5_cavite.cst

→ Quite good agreement between solvers
→ That agreement is necessary to trust the results
→ Errors visible on frequency (~20 MHz) and wake convergence
Cavity impedance: what should be watched?

- Low frequency contribution in particular before the first main resonant modes (impact proportional to the sum of \( R/Q \) of all modes)
- Resonant modes themselves (impact proportional to \( R \))

→ True for longitudinal and transverse impedance contributions
→ How can we reduce these contributions?
Mitigating cavity modes?

- Changing the shape
- Changing the material
- Using taperings
- Shielding the cavity with RF fingers
Mitigating cavity modes: changing dimensions

• Simulate changes of radius and length of the cavity

• File: 5_cavity_dimensions.cst
Outcome (1)

• Q factors more or less constant
• Reducing the diameter clearly helps with reducing the shunt impedance R
Outcome (2)

• Changing the length: the cavity should be very short or very long, but avoid the order of magnitude of the radius.
Mitigating cavity modes?

• Changing the shape

• Changing the material

• Using taperings

• Shielding the cavity with RF fingers
Mitigating cavity modes: changing materials

[note the parameter sweep does not work].

Change the conductivity of the material from 1e6 S/m to 1e7 S/m.

→ Q factors and shunt impedances R scale both with $\sqrt{\sigma}$
→ R/Q depends little on the material, but R can be reduced by increasing material losses
→ If losses are deliberately generated by decreasing Q and R, the lossy material should be able to sustain the remaining power loss
Mitigating modes: adding tapers

→ Tapers help but do not suppress the modes
Mitigating modes: shielding with RF fingers
Mitigating modes: shielding with RF fingers

![Diagram of shielding with RF fingers]

**Non touching finger**

**Conform finger**

**Graph:**
- **Shunt impedance in LinacOhm** vs. **Frequency in GHz**
- Two curves:
  - Red dots: Frequency (Multipl...(angle=5)
  - Green triangles: Frequency (Multipl...(angle=0)
Mitigating modes: shielding with RF fingers

→ In case of non conformities: finger not touching

Could be much worse than the situation without fingers!
Recommendation: use funneling
Assignment #2

• Consider two sets of 2 vacuum tubes that need to be connected by a bellow (diameter of 7 mm and 18 mm).
• Find for each case a suitable tradeoff between mechanical and impedance constraints
Final remarks

If you held until the end, you are welcome in the impedance team!
Bellows

• Theory: K. Ng [http://lss.fnal.gov/archive/fn/FN-0449.pdf]
• Complications:
  • beyond cutoff
  • Beta<1
Confusion with electrical impedance?

- Ohm’s law:
  \[ U = Z \cdot I \quad \text{Power loss: } P = Z \cdot I^2 \]

- Longitudinal beam coupling impedance
  \[ \Delta Q_{\text{long}} \propto Z_{\text{long}} \cdot I_{\text{beam}} \quad \text{Power loss: } P \propto Z_{\text{long}} \cdot I_{\text{beam}}^2 \]

- Transverse beam coupling impedance
  \[ \Delta Q_{\text{trans}} \propto Z_{\text{trans}} \cdot I_{\text{beam}} \]
Effect of conductivity of coating

→ For small thickness, very little impact of conductivity on transverse effective impedance!
→ Trade-off between bad conductivity and small thickness can be found