RF Impedance measurements versus simulations

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Radio-frequency bench measurements nowadays represent an important tool to estimate the coupling impedance of any particle accelerator device.

The well-known technique based on the coaxial wire method allows to excite in the device under test a field similar to the one generated by an ultra-relativistic point charge. Nevertheless the measured impedance of the device needs comparisons to numerical simulations and, when available, theoretical results.

We discuss the basics of the coaxial wire method and report the formulae widely used to convert measured scattering parameters to longitudinal and transverse impedance data. We will discuss typical measurement examples of interest for the LHC.

In case of resonant structures, impedance measurements and comparison with simulations become easier. The bead-pull technique may be used in this case.
Outline

Basic definitions

Coaxial wire method: motivation and validation
  - Longitudinal coupling impedance
  - Transverse coupling impedance
  - Other applications: trapped modes finding

Impedance for resonant structures

Conclusion
Basic definitions

\[ Z_{\parallel}(\omega) = -\frac{1}{q} \int_{-\infty}^{\infty} E_z (r = 0; \omega) \exp \left( j \frac{\omega}{c} z \right) dz \quad (\Omega) \]

\[ Z_{\perp}(\omega) = \frac{j}{q^2} \int_{-\infty}^{\infty} \frac{F_{\perp} (r_1, r_2; \omega)}{r_1} \exp \left( j \frac{\omega}{c} z \right) dz \quad (\Omega/m) \]

Impedance of most element of the LHC is carefully optimized (measurements and simulations).

Impedance data stored in a database to derive the impedance model of the machine and eventually compute instability thresholds.

L. Palumbo, V. Vaccaro, M. Zobov, LNF-94/041
Simulation tools

General purpose (3D) codes

- MAFIA, GDFDL
- HFSS, MW studio, ...

Wake potentials
- YES

2D codes: MAFIA2D, SUPERFISH, OSCAR2D ...

Impedance dedicated codes (2D): ABCI, ...
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Field in the DUT with/without wire:
a cylindrical waveguide (beam pipe)

Ultra-relativistic beam field

TEM mode coax waveguide

\[ E_r(r, \omega) = Z_0 H_\varphi(r, \omega) = \frac{Z_0 q}{2\pi r} \exp \left( -j \frac{\omega}{c} z \right) \]

\[ E_r(r, \omega) = Z_0 H_\varphi(r, \omega) = Z_0 \frac{\text{const}}{r} \exp \left( -j \frac{\omega}{c} z \right) \]

Device Under Test

Coaxial wire

Single wire centered/displaced Two wires
Field in the DUT with/without wire: a cylindrical waveguide (beam pipe)

Ultra-relativistic beam field

\[ E_r(r, \omega) = Z_0 H_\varphi(r, \omega) = \frac{Z_0 q}{2\pi r} \exp\left(-j\frac{\omega}{c}z\right) \]

TEM mode coax waveguide

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TM01 mode in a coax waveguide (above cut-off)

\[ E_z(r) / E_{z,cyl}(0) \]

\( a \to 0 \)

Cylindrical guide

\( r/b \)

\( 0 \) \( 0.2 \) \( 0.4 \) \( 0.6 \) \( 0.8 \) \( 1 \)

\( 0 \) \( 0.2 \) \( 0.4 \) \( 0.6 \) \( 0.8 \) \( 1 \)
EPA experiment: beam set-up

Goal of the experiment: to investigate the transmission properties of a coated ceramic chamber with the CERN EPA electron beam.

Titanium coating (1.5 µm)
Thickness << skin depth
DC resistance 1 Ohm

Reference chamber
(non coated)

500 MeV electron bunch
(7e10 particles, σ~ 1 ns)

EPA 1999: shielding properties
EPA 2000: effect of external shields

L. Vos et al., AB-Note-2003-002 MD
EPA experiment: bench set-up

The same ceramic chambers used in the beam experiment have been measured within a coaxial wire set-up, using the same magnetic field probes.

VNA with time domain option

wire diameter: 0.8 mm
Matching resistors: 240 Ohm

Synthetic pulse (300 MHz BW)

Just like in the early days of coaxial wire techniques (Sand and Rees, 1974)
Bench vs beam measurement in EPA

The external shield is electrically connected to the vacuum chamber.

Beam/wire axis

Vacuum chamber

External shield

Titanium coating

Ceramic chamber

Field probe
Bench vs beam measurement in EPA

The external shield carries image currents and field penetrates the thin resistive (titanium) layer if this external bypass is present.

The two signals are normalised and shifted such that this point is the same.
Bench vs beam measurement in EPA

Shielding properties of the coated chamber

“Naked” coated chamber

EPA, 2000

In the ref. chamber the probe is inside a brass shielding (connected to ground).
Bench vs beam measurement in EPA

Shielding properties of the coated chamber

Bench meas.

300 MHz Bandwidth

EPA, 2000

Normalized signals

Reference Chamber
Coated Chamber

Input Power 10 dBm
In the ref. chamber the probe is inside a brass shielding (connected to ground).
The shielding properties of thin metallic layers of finite length are important for LHC (fast kickers, silicon detectors).

Beam electric field can penetrate through infinitely long metallic layers of thickness much smaller than the skin depth.

Bench measurements (coaxial wire) on a kicker prototype suggested that finite thin layer have different shielding properties from infinitely long ones. Numerical (HFSS) studies predicted the shielding properties of a finite length thin layer (PAC 99).

Beam measurements assess the shielding properties but show that they can be spoiled by the addition of a second layer.

Coaxial wire bench measurements on the chambers used in the beam line confirmed later the experiment conclusions.
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Transmission line model

\[ \text{DUT} + \text{Coaxial Wire} = \text{TEM transmission line (with distributed parameters)} \]

The DUT coupling impedance is modeled as a series impedance of an ideal REFerence line.

Coupling impedance is obtained from the REF and DUT characteristic impedances and propagation constants.

Transmission line are characterized via S-parameters with Vector Network Analysers (transmission measurements preferred).

In the framework of the transmission line model, the DUT impedance can be computed from S-parameters.

\[ \downarrow \quad \downarrow \quad \downarrow \]

Practical approximated formulae

Review: F. Caspers in Handbook of Accelerator Physics and Engineering (‘98)
**Coupling impedance formulae**

**Improved log formula (Vaccaro, 1994)**

\[
Z_{LOG} = -Z_c \ln \left( \frac{S_{21}^{DUT}}{S_{21}^{REF}} \right) \left[ 1 + \frac{\ln (S_{21}^{DUT})}{\ln (S_{21}^{REF})} \right]
\]

Small Impedance wrt to Zc

**Log formula (Walling et al, 1989)**

\[
Z_{log} = -2Z_c \ln \left( \frac{S_{21}^{DUT}}{S_{21}^{REF}} \right)
\]

**Hahn-Pedersen formula (1978)**

\[
Z_{HP} = -2Z_c \frac{S_{21}^{DUT} - S_{21}^{REF}}{S_{21}^{DUT}}
\]

Lumped element: DUT length << λ

Already implemented in the conversion formula of modern VNA

**Systematic errors are discussed in**

E. Jensen, PS-RF-Note 2000-001 (2001)

H. Hahn, PRST-AB 3 122001 (2001)
Systematic errors in the formulae

H. Hahn, PRST-AB 3 122001 (2001)

\[ Z_{\parallel} \quad \text{Beam coupling impedance} \]

\[ \frac{Z_{HP}}{Z_{\parallel}} \approx 1 + \frac{Z_{\parallel}}{4Z_c} \left[ 1 + \frac{j}{\Theta} - \frac{(1 - e^{-j\Theta}) e^{-j\Theta}}{\Theta^2} \right] \]

\[ \Theta = \beta L \rightarrow \frac{L}{\lambda} \]

The error is always proportional to \( \frac{Z_{\parallel}}{Z_c} \)

Thin wire \( \rightarrow \) High Zc

E. Jensen, PS-RF-Note 2000-001 (2001)

Compares the three formulae to the exact transmission line solution.

The wire method is strictly valid for frequencies below cut-off.
MKE kicker measurements


$L=2.31\ m$  \hspace{1cm}  $L_f=1.66\ m$

Coupling impedance $\gg$ characteristic impedance (300 Ohm)

Correction to the improved LOG formula:

$$Z_{LOG} = Z_{log} \left[ 1 + \frac{j\omega L_f}{2} \ln \left( \frac{S_{DUT}^{21}}{S_{REF}^{21}} \right) \right]$$

At low frequencies ($\lambda \sim L$), theory is closer to standard log formula.
A model for the LHC injection kicker

Ceramic test chamber with 30 printed conducting strips (different widths) inside, using the same technology of the final LHC kicker.

Copper tape surrounding the right end of the ceramic tube in order to make a capacitor between the right port and the strip line (point C).

HFSS simulation of the bench measurement


Current bypass conductor included.

Simplification: 12 strip lines with the same width.
Resonance @ 17.3 MHz (700 Ohm) is due to the capacitor and the inductance created by the strip and the outer support. To dump it a ferrite ring was set (agreement between measurement and simulations).

Resonance @ 30 MHz is a transverse resonance and it may be related to slightly offset or not properly tightened wire.
The 442.3 MHz and 846.4 MHz peaks are due to coaxial waveguide resonance at the copper tape.
Longitudinal coupling impedance bench measurements are reasonably well understood but not always “easy” and the technique is “well established”.

With modern simulation codes, one can derive directly the coupling impedance or simulate the bench set-up with wire, virtually for any structure.

Evaluation of coupling impedance from measured or simulated wire method results require the same cautions.

Simulations and RF measurements usually agree well.

Comparison with numerical results are very useful to drive and to interpret the measurements.

Simulation may require simplified DUT model which should reproduce the main DUT electromagnetic features.
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Transverse impedance measurements

The transverse impedance is proportional (at a given frequency) to the change of longitudinal impedance due to lateral displacement of the beam in the plane under consideration (H or V): Panowsky-Wentzel theorem.

Two parallel wires are stretched across the DUT (odd mode).

Panowsky-Wentzel
Two wires/loop

\[ Z_\perp = \frac{Z_\parallel C}{\omega \Delta^2} \]

\(\Delta\) wire spacing (~10% of the DUT radius)

\[ Z_{\perp,LOG} = -\frac{Z_c c}{\omega \Delta^2} \ln \left( \frac{S_{21}^{DUT}}{S_{21}^{REF}} \right) \left[ 1 + \frac{\ln (S_{21}^{DUT})}{\ln (S_{21}^{REF})} \right] \]

from improved log formula

\[ Z_c = Z_c, ODD \]

At low frequency:
\(\lambda >>\) DUT length

Lumped element formula

Traditional approach: Nassibian-Sacherer (1977), ...
Low frequency transverse impedance

\[ Z_T = \frac{c \, Z_{DUT} - Z_{perf. \, cond.}}{\omega \, N^2 \Delta^2} \]

\( \Delta \) loop width \( N \) # turns
Low frequency transverse impedance

A “calibration” case: circular steel beam pipe

radius = 50 mm
\( \sigma = 1.3 \times 10^6 \text{ S/m (SS)} \)
wall thick. = 1.5 mm
\( L_D = 2 \text{ m} \)

\( L_W = 1.25 \text{ m} \)
D = 22.5 mm
\( N = 10 \)

\[ Z_T = \frac{c}{\omega} \left( \frac{Z_{DUT} - Z_{perf. \, cond.}}{N^2 \Delta^2} \right) \]

\( \Delta \) loop width \( N \) # turns
Steel pipe: real transverse impedance

Real impedance vanishes at DC (no variation of the long. imp. with position).
The reference measurement can be done in free space.
Steel pipe: imaginary transverse imp.

The reference measurement must be done in a “perfectly” conducting pipe. This technique is currently used (e.g. in SNS kicker measurements).
Single displaced wire or two wires?

In the two wires bench set-up only “dipole field components”: no longitudinal electric field components on axis (metallic image plane between wires).

Some devices exhibit a strong azimuthal asymmetry in the image current distribution due to variation of the conductivity (e.g. ferrite in kickers) or to the cross section shape.

In order to get a more complete view of the transverse kick on the beam, it may be useful to characterize the device with a single wire.

H. Tsutsui, SL-Note-2002-034 AP

Measuring transverse impedance with a single displaced wire.

Panowsky-Wentzel theorem

\[ Z'_\perp = \frac{c}{\omega} \nabla \perp Z_\parallel \]

Variation of the longitudinal impedance as a function of displacement for a single wire.

\[ Z_\perp \approx \frac{c}{\omega} \frac{Z_\parallel (x_0) - Z_\parallel (x_0 = 0)}{x_0^2} \]
Transverse impedance measurement technique are more delicate particularly for asymmetric devices (TW kickers like SPS MKE).

New measurement procedures oriented to particular DUTs are being proposed (e.g. SNS kicker measurements, H. Hahn 2004).

Numerical simulations are necessary to control measurement procedure.

Schematic model of DUT feasible for simulations should not introduce non physical symmetries or approximation.
Trapped modes finding

A coaxial wire set-up can be used to study the behavior of a given DUT when passed through by a relativistic beam (e.g. see if trapped mode is excited, beam transfer impedance).

MAFIA simulations were showing a small trapped mode in some LHC IR.

To understand better, simulations on approximated (rectangular) geometries were carried out and they showed stronger resonance peaks.

CERN, LBNL, LNF-INFN collaboration, NIMA 517 (2004)
Measurement feasibility study: HFSS

Idea: excite the trapped mode with a coaxial wire in a scaled (simple) rectangular prototype.

a = 66 mm  b = 18 mm  c = 85 mm
Measurement feasibility study: HFSS

Idea: excite the trapped mode with a coaxial wire in a scaled (simple) rectangular prototype.

\[ a = 66 \text{ mm} \quad b = 18 \text{ mm} \quad c = 85 \text{ mm} \]

\[ S_{12} \rightarrow 1 \quad \text{“No” impedance} \]
Measurement feasibility study: HFSS

Idea: excite the trapped mode with a coaxial wire in a scaled (simple) rectangular prototype.

a = 66 mm, b = 18 mm, c = 85 mm

$s_{12} \rightarrow 1$ “No” impedance

$S_{12} \rightarrow 0$ Trapped mode
MAFIA predictions for bench set-up

The wire does not introduce a significant perturbation of this trapped mode, in this case as seen by comparison between HFSS (wire) and MAFIA (no wire).
Measurement set-up and results

<table>
<thead>
<tr>
<th>MAFIA</th>
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Measurement set-up and results

Tapering the transition, as in the actual geometry strongly reduces the effect of this trapped mode.

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Wire perturbs *longitudinal* cavity modes, e.g. lowering the Q and detuning the frequency: coaxial wire set-ups are not recommended for cavity measurements (only special cases, mainly transverse).

**Bead Pull measurement**

The field in a cavity can be “sampled” by introducing a perturbing object and measuring the change in resonant frequency.

The object must be so small that the field do not vary significantly over its largest linear dimension: it is a perturbation method.

Shaped beads are used to enhance perturbation and give directional selectivity.
The measurement technique

Slater theorem

Only longitudinal electric field

\[ \frac{f_p - f_0}{f_0} = -\Delta V \varepsilon_0 k_E \frac{E_z^2}{4U} \]

Form factor can be calculated for ellipsoid or calibrated in known fields (e.g. TM_{0n0} of a pillbox cavity).

The frequency variation can be measured by the variation of the phase at the unperturbed resonant frequency (very precise initial tuning needed!).

\[ \frac{f_p - f_0}{f_0} = \frac{\tan \phi(f_0)}{2Q_L} \sim \frac{\phi(f_0)}{2Q_L} \]

Transmission measurement

It allows visualizing the field shape on the VNA screen.
An 11 GHz cavity for SPARC

Standing wave accelerating cavity ($\pi$ mode)

Correction of linac RF voltage

9 cells prototype

Resonance frequency: 11.424 GHz

$r = 1.0477$ cm
(End Cell)

$R = 1.0540$ cm
(Central Cells)

$r = 1.0477$ cm
(End Cell)

$p = 1.3121$ cm
$t = 0.2$ cm

Iris radius = 0.4 cm

End cells radius is reduced (0.6%) to achieve a flat axial field
An 11 GHz cavity for SPARC

Standing wave cavity (π mode)

Correction of linac RF voltage

Resonance frequency: 11.424 GHz

End cells radius is reduced (0.6%) to achieve a flat axial field
Irregularities of the nylon wire used to carry the bead, do have an effect. Lower frequency measurement (3 GHz) do not show such effect.
11 GHz cavity: accelerating field

$E_z / \sqrt{U}$

$10^8 V/\mu m/\sqrt{J}$

z axis (cm)
11 GHz cavity: accelerating field

\[ E_z / \sqrt{U} \]

$10^8 \text{V/mVJ}$

HFSS
SuperFish

z axis (cm)
11 GHz cavity: accelerating field

The graph shows the normalized electric field $E_z / \sqrt{U}$ as a function of the z-axis position (cm). The graph compares the results from different software tools:

- Green line: HFSS
- Purple line: SuperFish
- Black line: Mafia

The x-axis represents the z-axis position in centimeters, while the y-axis represents the normalized electric field in units of $10^8 V/\sqrt{m}\sqrt{J}$. The graph exhibits a periodic pattern with a wavelength corresponding to the wavelength of the 11 GHz cavity.
11 GHz cavity: accelerating field

\[ \frac{R/Q}{L} = \left| \int_0^L E_z(z) \exp \left( j \frac{\omega}{c} z \right) dz \right|^2 \frac{1}{U \omega L} \]

<table>
<thead>
<tr>
<th>HFSS</th>
<th>SuperFish</th>
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<th>Measur.</th>
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<td>9138</td>
<td>9232</td>
<td>9392</td>
<td>9440 (87)</td>
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(Ω/m)

RF measurements vs simulations: resonant cavities

For resonant structure accurate measurements are “easy”, provided understanding of bench set-up details (e.g. glue effect in 11 GHz measurements).

Very good agreement between measurement and simulations.

Bead pull measurements are used to see if the DUT fits the design specifications and still required for tuning multiple cell cavities.

Q measurement on a cavity has precision better than 1%.

R/Q is usually done with computer codes, measurement are often only confirmations.
Conclusions

The most common methods of measuring coupling impedance: wire method (long. and trans. impedance) and bead pull method (resonant structures).

There are several codes usable to estimate coupling impedances (MAFIA, HFSS, GDFDL, MWstudio, ABCI, OSCAR2D, Superfish …).

Impedance can be computed by numerical RF simulators or directly or by simulating the wire measurement.

Numerical simulations often deal with simplified models: i.e. you must have some insight in the problem.

With a reasonable and accurate modeling, a longitudinal impedance simulation usually reproduce experimental results (and viceversa).

Transverse impedance requires a much deeper control of both simulations and bench measurements, particularly for some special devices.

Impedances of resonant modes are well reproduced by simulation with high reliability.
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Thank you for your attention