Beam coupling impedance of the new LHC collimators

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General outline

- Introduction
- LHC Run II TCS/TCT features
- Kick factors estimations
- Study of material properties for GdfidL simulations¹
  - Resistive wall
  - TT2-111R dispersive properties
- LHC Run II TCS/TCT impedance study, HOMs characterization and comparison with measurements
- Conclusions

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The LHC collimators’ hierarchy

A multi-stage beam cleaning system

- Beam halo cleaning throughout the LHC beam cycle (99.998% of efficiency)
- Machine aperture passive protection against radiation (hardware)
- Halo diagnostics and tails scraping
- SC magnets protection against quenching

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The LHC collimators’ hierarchy

A multi-stage beam cleaning system

Functionalities

- Beam halo cleaning throughout the LHC beam cycle (99.998% of efficiency)
- Machine aperture passive protection against radiation (hardware)
- Halo diagnostics and tails scraping
- SC magnets protection against quenching
The importance of impedance study in beam dynamics

**As a general remark**

\[
Z_\parallel(\omega) \equiv \frac{1}{c} \int_{-\infty}^{\infty} W_\parallel(z)e^{-i\frac{\omega}{c}z}dz; \quad [\Omega] \tag{1}
\]

\[
Z_\perp(\omega) \equiv \frac{i}{c} \int_{-\infty}^{\infty} W_\perp(z)e^{-i\frac{\omega}{c}z}dz; \quad [\Omega/m] \tag{2}
\]

- Collective effects are *intensity dependent* \(\Rightarrow\) the higher the currents the stronger the parasitic heating and the beams’ instabilities \(\Rightarrow\) beam lifetime and beam quality degradation

- Short range wake fields affect *single bunch* instabilities (e.g. Transverse Mode Coupling Instability); long range wakes affect *multi bunch* instabilities (e.g. Coupled Bunch Instability) \(\Rightarrow\) HOMs damping in cavity structures is mandatory

- Collimators are among the main beam coupling impedance contributors!
What our work aims at..

Our goal is to simulate the complicated 3D collimator structures as close as possible to their real design

- Using CAD drawings and billions of mesh points
- Properties of real materials
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The LHC Run II BPM embedded collimator design

RF fingers are removed from the previous LHC Run I TCS/TCT design. HOMs damping provided by TT2-111R ferrite blocks.

It was already shown that the transverse effective impedance was expected to increase of about 20% wrt LHC RUN I no BPM pickup button collimator design.

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3 Frasciello, O. and others. Wake fields and impedances of LHC collimators. Invited talk at 100th National Congress of the Italian Physical Society (SIF), 22 - 26 September 2014, Pisa, Italy. 2014.
L=30 cm, a=5 mm, b=10 mm, \( \sigma = 7.69 \cdot 10^5 \) S/m

The length is chosen in order to minimize ends contributions
Resistive insert

For Azimuthally Symmetric Thick Resistive Walls

Longitudinal Loss factor

\[ k_{||} = \frac{cL}{4\pi b\sigma^{3/2}} \sqrt{\frac{Z_0 \rho}{2}} \Gamma \left( \frac{3}{4} \right) \]

Transverse kick factor

\[ k_{\perp} = \frac{cL}{\pi^2 b^3} \sqrt{\frac{2Z_0 \rho}{\sigma_z}} \Gamma \left( \frac{5}{4} \right) \]

Loss and Kick factors benchmark: GdfidL vs. Analytical formulas

Some excess in Kicks may be due to the rough mesh
Results are shown down to $\sim 10$ MHz because this is the frequency range of interest up to now. We also got results down to fractions of MHz (not shown here).
Simulation of $S_{11}$ measurement setup

In our opinion it was a very useful method to arrange simple coaxial probe measurement simulations, in order to check for the numerically computed S-parameters to be fully in agreement with theoretical prediction.

Measurement layout (From R. Boni et al., LNF-93/014)

Simulated measurement

Analytical formulas

\[ S_{11} = \frac{\Delta \cdot \tanh(\gamma L) - 1}{\Delta \cdot \tanh(\gamma L) + 1}; \]
\[ \gamma = j \omega \sqrt{\varepsilon \mu}; \]
\[ \Delta = \sqrt{\frac{\mu_r}{\varepsilon_r}} \]
Simulation of $S_{11}$ measurement setup

$\mu$ experimental data (Courtesy of B. Salvant) & GdfidL DUT model

Data fits with $n^{th}$ order Lorentz function & $S_{11}$ results comparison

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TT2-111R ferrite loaded pillbox

The simple pillbox geometry

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An overall damping feature is shown to be proper of the structure made by resistive Tungsten jaws plus ferrite blocks.
The low frequency modes grow with the offset

The low frequency peaks clearly correspond to transverse modes
**BPM TCS-TCT:** $Z_\perp$ simulations vs loop meas w/ ferrite

**GdfidL computed modes**

<table>
<thead>
<tr>
<th>i</th>
<th>f [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>84.0</td>
</tr>
<tr>
<td>2</td>
<td>169.0</td>
</tr>
<tr>
<td>3</td>
<td>256.0</td>
</tr>
</tbody>
</table>

Measurements data and plots courtesy of N. Biancacci
BPM TCS-TCT: $Z_{\perp}$ simulations vs wire meas w/o ferrite

Measurements data courtesy of N. Biancacci
Measurements data
courtesy of N. Biancacci
All HOMs found to correspond to those measured with loop (w/ ferrite) and with single wire (w/o ferrite) at the same frequencies.

The $R_s$ of the first HOM is about 2 times higher than that obtained by CST (1.5 M$\Omega$/m) for the same half gap.

Results may depend on:
- the gap between the plate where ferrite blocks are installed (HOMs frequencies shifts of the order of tens %);
- the gap between collimator jaw and tank (HOMs $R_s$);
- mesh and computed wake length.

A strong damping feature of the ferrite is exhibited at all frequencies.

Adding ferrite blocks, HOMs’ frequencies shift down and their $R_s$ are damped; e.g. for the first HOM, the characteristic frequency shifts from $\approx 95$ to $\approx 84.5$ MHz, whereas the $R_s$ is damped from $\approx 340$ k$\Omega$/m to $\approx 237$ k$\Omega$/m;

the wake has a stronger and better convergence, within the computed range of 200 m, for the collimator with ferrite, as expected.
The performed numerical tests have confirmed that GdfidL reproduces very well the properties of the lossy dispersive materials. The simulation test results for the resistive walls and the lossy ferrites are in a good agreement with available analytical formulae and the results of other numerical codes and semi-analytical models.

The numerical studies of the impedance of the new LHC collimators with incorporated BPMs have shown that:

I The longitudinal higher order modes till 1.2 GHz are heavily damped by the TT2-111R ferrite blocks and by the resistive contribution of the jaws. This is very important for the heating reduction of the collimators in the multibunch regime (for the nominal LHC bunches 7.5 cm long);

II The transverse modes at low frequencies are less damped, there are still residual transverse HOMs at frequencies around 100 MHz and 200 MHz with non-negligible shunt impedances. The calculated frequencies of the modes are in remarkable agreement with the loop measurements. The shunt impedances of the modes obtained numerically agrees within a factor of 2 with the experimental data of the wire measurements performed by the CERN impedance group;

III The broad-band transverse impedance of the new double taper collimators are evaluated to be approximately by 20% higher with respect to that of the single taper secondary collimators.

The calculated impedance of the new collimators is required for the update of the LHC impedance model used to estimate the instabilities rise times, betatron tune shift with the beam current, eventual beam power losses etc.
Thanks for your kind attention

Acknowledgements: E. Metral, B. Salvant, N. Biancacci
W. Bruns, for his invaluable support
Backup slides
Tsutsui model for TT2-111R ferrite kicker

Kicker model in CST and GdfidL

Benchmark on Tsutsui kicker model $Z_{0}$

Benchmark on Tsutsui kicker model $Z_{0}$

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Tsutsui model for TT2-111R ferrite kicker

Benchmark on Tsutsui kicker model $Z_{\text{OPT}}$

Benchmark on Tsutsui kicker model $Z_{\text{QUAD}}$

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\( \varepsilon_r \) contribution to \( Z_{\parallel} \) and \( Z_{\perp} \) in Tsutsui models

For axisymmetric model:

\[
\frac{Z_{\parallel}}{L} \simeq (1-j) \frac{Z_0}{2\pi b} \sqrt{\frac{\mu_r''}{2\varepsilon_r'}}
\]

For rectangular model:

\[
\frac{Z_{\parallel}}{L} = j \frac{Z_0}{I_0} \sum_{n=0}^{\infty} \left[ \frac{k_{xn}}{k} (1+\varepsilon_r \mu_r) \text{sh} + \frac{k_{yn}}{k} (\mu_r \varepsilon_r^2 \text{sh} + \varepsilon_r \varepsilon_r' \varepsilon_r') \right] /
\frac{\varepsilon_r' \mu_r - 1}{k_{xn}} \text{sh}
\]

\[
\frac{Z_{\perp}^X}{L} = j \frac{Z_0}{2a} \sum_{n=0}^{\infty} \frac{k_{xn}}{k} \left[ \frac{k_{xn}}{k} (1+\varepsilon_r \mu_r) \text{sh} + \frac{k_{yn}}{k} (\mu_r \varepsilon_r^2 \text{sh} + \varepsilon_r \varepsilon_r' \varepsilon_r') \right] /
\frac{\varepsilon_r' \mu_r - 1}{k_{xn}} \text{sh}
\]

\[
\frac{Z_{\perp}^Y}{L} = j \frac{Z_0}{2a} \sum_{n=0}^{\infty} \frac{k_{xn}}{k} \left[ \frac{k_{xn}}{k} (1+\varepsilon_r \mu_r) \text{sh} + \frac{k_{yn}}{k} (\mu_r \varepsilon_r^2 \text{sh} + \varepsilon_r \varepsilon_r' \varepsilon_r') \right] /
\frac{\varepsilon_r' \mu_r - 1}{k_{xn}} \text{sh}
\]

In all above formulae:

\( \text{sh} = \sinh(k_{xn}b) \); \( \text{ch} = \cosh(k_{xn}b) \);

\( \text{tn} = \tan(k_{yn}(b-d)) \); \( \text{ct} = \cot(k_{yn}(b-d)) \)

\( \varepsilon_r = \varepsilon_r' - j \varepsilon_r' + \frac{\sigma}{j \omega \varepsilon_0} \)

\( \mu_r = \mu_r' - j \mu_r'' \)
Present TDI single segment geometry, one linear taper plus sharp discontinuity plus in & out 10 cm tubes, GdfidL wakefield simulations: $\sigma_z = 7.5$ cm, $s = 75$ cm.
New proposed TDI single segment geometry, one linear taper plus in & out 10 cm tubes, GdfidL wakefield simulations: $\sigma_z = 7.5$ cm, $s=75$ cm.
New suggested TDI single segment geometry, plus in & out 10 cm tubes, GdfidL wakefield simulations: $\sigma_z = 7.5$ cm, $s = 75$ cm.

A non linear taper is described by a function of the type

$$h(z) = \frac{h_{\text{min}}}{[1 + zL(\beta^{-\frac{1}{2}} - 1)]^2},$$

where $\beta \equiv \frac{h_{\text{max}}}{h_{\text{min}}}$.

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$^4$B. Podobedov and I. Zagorodnov, PAC2007, p. 2006
## Resulting parameters from GdfidL simulations

### PRESENT geometry (linear flat taper + sharp discontinuity)

<table>
<thead>
<tr>
<th></th>
<th>PEC</th>
<th>R4550 graphite ($\sigma_\infty = 7.64 \cdot 10^4$ S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_\parallel$ [V/C]</td>
<td>$1.73 \cdot 10^9$</td>
<td>$2.59 \cdot 10^9$</td>
</tr>
<tr>
<td>$Z_{\perp}(0)$ [kΩ/m]</td>
<td>$49.4$</td>
<td>$123.1$</td>
</tr>
<tr>
<td>$k_{\perp}$ [V/Cm]</td>
<td>$5.32 \cdot 10^{13}$</td>
<td>$1.37 \cdot 10^{14}$</td>
</tr>
</tbody>
</table>

### NEW geometry (only longer and higher linear flat taper)

<table>
<thead>
<tr>
<th></th>
<th>PEC</th>
<th>R4550 graphite ($\sigma_\infty = 7.64 \cdot 10^4$ S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_\parallel$ [V/C]</td>
<td>$1.59 \cdot 10^9$</td>
<td>$2.69 \cdot 10^9$</td>
</tr>
<tr>
<td>$Z_{\perp}(0)$ [kΩ/m]</td>
<td>$31.9$</td>
<td>$109.6$</td>
</tr>
<tr>
<td>$k_{\perp}$ [V/Cm]</td>
<td>$3.46 \cdot 10^{13}$</td>
<td>$1.21 \cdot 10^{14}$</td>
</tr>
</tbody>
</table>

### Alternative geometry (non linear taper)

<table>
<thead>
<tr>
<th></th>
<th>PEC</th>
<th>R4550 graphite ($\sigma_\infty = 7.64 \cdot 10^4$ S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_\parallel$ [V/C]</td>
<td>$1.61 \cdot 10^9$</td>
<td>$2.82 \cdot 10^9$</td>
</tr>
<tr>
<td>$Z_{\perp}(0)$ [kΩ/m]</td>
<td>$19.98$</td>
<td>$102$</td>
</tr>
<tr>
<td>$k_{\perp}$ [V/Cm]</td>
<td>$2.09 \cdot 10^{13}$</td>
<td>$1.11 \cdot 10^{14}$</td>
</tr>
</tbody>
</table>
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TDI new model first follow-up
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