The impedance budget of the CERN Proton Synchrotron (PS)

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Why do we study the beam impedances?

In order to understand the beam dynamics of an accelerator machine that is part of an injector chain, it is important to assess its impedance model: to increase the energy of LHC, the impedances of all injectors have to be well known!

The current knowledge of the longitudinal and transverse impedance of the CERN Proton Synchrotron (PS) is established with electromagnetic simulations, theoretical computations and beam-based measurements.

Proton Synchrotron: 628 meters long 100 straight sections Injection at 1.4 GeV Extraction at 26 GeV
Vertical impedance is critical respect to horizontal impedance because of the “elliptical” shape of the PS beam chamber!
How we assess the transverse impedance budget?

Tune shift measurements

For a Gaussian bunch with rms bunch length $\sigma_z$, the tune shift $\Delta Q$ is proportional to the imaginary part of the transverse effective impedance $Z_T^{eff}$ by:

$$\Delta Q = \frac{\beta e I_0}{4\sigma_z \sqrt{\pi} \omega_0^2 Q_0 \gamma m_0} \text{Im}\{Z_T^{eff}\}$$

**NB:** The differences in the two sets of measurements in the vertical plane can be explained by the coherent space charge effect.
Kickers magnets

RF cavities
- 200 MHz complex
- 40 and 80 MHz cavities
- Ferrite loaded: 10 MHz, Finemet cavity

Vacuum components
- Features in the PS beam line
- Sector valves

Comparison with measurements
Agenda

- Kickers magnets
  - RF cavities cavities
    - 200 MHz complex
    - 40 and 80 MHz cavities
    - Ferrite loaded: 10 MHz, Finemet cavity
  
- Vacuum components
  - Features in the PS beam line
  - Sector valves

- Comparison with measurements
Examples of kickers in the PS

Kickers are the main source of impedance in the Proton Synchrotron: their presence can explain about the 15% of the vertical impedance measured at 2 GeV!
Agenda

- Kickers magnets
- RF cavities
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  - Sector valves
- Comparison with measurements
200 MHz cavity: 3D model

**Wakefield simulations**

**Step 1.**

Generation of the “naked cavity”
tuned with 4 cylindrical tuners

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>$R_s$ (kΩ)</th>
<th>R/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>199.9 MHz</td>
<td>6,180</td>
<td>174 kΩ</td>
<td>28.2</td>
</tr>
</tbody>
</table>

**Step 2.**

Output coupler oriented of 38º

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>$R_s$ (kΩ)</th>
<th>R/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>199.3 MHz</td>
<td>2,013</td>
<td>55 kΩ</td>
<td>27.6</td>
</tr>
</tbody>
</table>
Modeling of the magnetic output coupler

200 MHz mode magnetic field lines

The output coupler has to couple the magnetic field line in order to reduce the Q factor of the resonance: the output coupler is oriented in order to diminish the Q from 6,000 to 1,900.
200 MHz cavity: 3D model

Input coupler oriented of 180°

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>$R_s$</th>
<th>R/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>199.9 MHz</td>
<td>1.094</td>
<td>30 kΩ</td>
<td>27.4</td>
</tr>
</tbody>
</table>

3 PIN lines for electric coupling

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>$R_s$</th>
<th>R/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>199.9 MHz</td>
<td>40</td>
<td>1.03 kΩ</td>
<td>27.3</td>
</tr>
</tbody>
</table>

NB: to extract resonant parameters of the cavity, simulations (with ports) have been performed with the Wakefield solver!
Ferrite loaded cavities

New CST release allows to simulate with the Eigenmode solver ferrite loaded cavities!

10 MHz cavity

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.44 MHz</td>
<td>1.4</td>
<td>2.1 kΩ</td>
</tr>
</tbody>
</table>

Finemet cavity

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.39 MHz</td>
<td>0.6</td>
<td>?</td>
</tr>
</tbody>
</table>

*Finemet cavity impedance studies*, S. Persichelli, M. Paoluzzi, M. Migliorati, B. Salvant CERN-ACC-NOTE-2013-0033. - 2013
RF cavities generation from 2D models

Why we need the 3D model

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>$R_s$</th>
<th>R/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.99 MHz</td>
<td>7,027</td>
<td>456 kΩ</td>
<td>32.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Freq</th>
<th>Q</th>
<th>$R_s$</th>
<th>R/Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.36 MHz</td>
<td>55,538</td>
<td>2.25 MΩ</td>
<td>60</td>
</tr>
</tbody>
</table>

Capacitive coupling

40 MHz

80 MHz
- RF cavities are not predicted to have a strong impact on the transverse impedance: they can explain less than 1% of the vertical impedance measured at 2 GeV.

- As an output of the impedance studies, now 3D models are available for the first time for all PS cavities!
Kickers magnets
RF cavities cavities
  200 MHz complex
  40 and 80 MHz cavities
  Ferrite loaded: 10 MHz, Finemet cavity
Vacuum components
  Features in the PS beam line
  Sector valves
Comparison with measurements
Vacuum equipment and features in the Proton Synchrotron beam line like pumps, valves, bellows, flanges, steps and misalignments are included in the model as distributed elements.

<table>
<thead>
<tr>
<th>Pumps</th>
<th>100</th>
<th>Sector valves</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flanges</td>
<td>259</td>
<td>Bellows</td>
<td>~200</td>
</tr>
<tr>
<td>Steps</td>
<td>~60</td>
<td>Misalignments</td>
<td>3</td>
</tr>
</tbody>
</table>
Vacuum equipment: sector valves

Wakefield simulations

Even if the impedance of the single element is small, the sum of many distributed elements explain about the 5% of the vertical impedance measured at 2 GeV.
Agenda

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  - 200 MHz complex
  - 40 and 80 MHz cavities
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  - Features in the PS beam line
  - Sector valves
- Comparison with measurements
- The purpose of simulation studies is to reach the measured value adding the impedances of single machine elements.

- Till now, about the 60-70% of the impedance measured at 2GeV, has been explained.

- The study is ongoing: several elements (wire scanners, pickups, septa, flanges) are going to be added to the current budget.
The imaginary part of the effective transverse impedance of the CERN Proton Synchrotron has been evaluated by tune shift measurements at different energies.

The transverse effective impedance has been also evaluated with CST Particle Studio and Microwave Studio simulations: from this budget we are still missing about 30-40% on the vertical plane.

A reasonable agreement between measurements and impedance budget has already been obtained on the longitudinal plane.

There are still many others elements to be added to the current impedance budget: the study is ongoing!
Thank you for your attention