Update on the FCC-hh impedance budget
Effective impedances

1) \[
\text{Im} Z_{\text{element}}^{\text{eff}}_{x,y} \text{TMCI} = \frac{\beta_{\text{element}}}{\langle \beta \rangle_{\text{smooth}}} \sum_{k=-\infty}^{k=\infty} \text{Im} Z_{\text{element}}^{\text{elec}}(\omega_k) h_{0,0}(\omega_k)
\]

2) \[
\text{Re} Z_{\text{element}}^{\text{eff}}_{x,y} \text{TCBI}_{m=1} = \frac{\beta_{\text{element}}}{\langle \beta \rangle_{\text{smooth}}} \max_n \left( \sum_{k=-\infty}^{k=\infty} \text{Re} Z_{\text{element}}^{\text{elec}}(\omega_k^n) h_{1,1}(\omega_k^n) \right)
\]

3) \[
\text{Re} Z_{\text{element}}^{\text{eff}}_{x,y} \text{TCBI}_{m=0} = \frac{\beta_{\text{element}}}{\langle \beta \rangle_{\text{smooth}}} \sum_{k=-\infty}^{k=\infty} \text{Re} Z_{\text{element}}^{\text{elec}}(\omega_k) h_{0,0}(\omega_k)
\]

4) \[
\text{Im} Z_{\text{element}}^{\text{eff}}_{n} \text{Loss of Landau} = \sum_{k=-\infty}^{k=\infty} k \text{Im} Z_{\text{element}}^{\text{elec}}(k \Omega_0) \Lambda_0(k \Omega_0)
\]

\[
\sum_{k=-\infty}^{k=\infty} k^2 \Lambda_0(k \Omega_0)
\]

Parabolic bunch

https://impedance.web.cern.ch/impedance/fcchh/impedances.html

New
Cold beamscreen + TiN or Carbon coatings

<table>
<thead>
<tr>
<th>Element</th>
<th>TCBI effective impedance, rigid bunch (head-tail mode 0), MOhm/m (definition)</th>
<th>TCBI effective impedance, head-tail mode 1, MOhm/m (definition)</th>
<th>TMCI effective impedance, MOhm/m (definition)</th>
<th>Loss of Landau damping effective impedance, mOhm (definition)</th>
</tr>
</thead>
</table>
| Without surface treatment | Negligible | Inj: 1.46 (x) / 2.69 (y)  
Top E: 1.96 (x) / 3.62 (y) | Inj: 6.11  
Top E: 7.88 | |
| TiN coating (200nm) | Negligible | Negligible | Inj: 34% of untreated cold beamscreen  
Top E: 26% of untreated cold beamscreen | Inj: 80% of untreated cold beamscreen  
Top E: 62% of untreated cold beamscreen |
| Carbon coating (200nm) | Negligible | Negligible | Inj: 34% of untreated cold beamscreen  
Top E: 26% of untreated cold beamscreen | Inj: 80% of untreated cold beamscreen  
Top E: 62% of untreated cold beamscreen |

**Allowed total budget**

- Inj: -1350  
Top E: -2050 or -4100  
Assuming $N_B=10^{11}$ and number of turns allowed by the feedback $n=60$ (Inj) and $n=600$ or 300 (Top E, the value depends on how aggressive the feedback will be)  
To be determined based on feedback.

- Inj: 12  
Top E: 70  
Assuming $N_B=3 \times 10^{11}$, RF voltage of 12 MV (Inj) / 32 MV (Top E), $N_S=0.65$  
Assuming the mechanism of loss of Landau damping as derived by Elena.

**New:**
- TCBI m=0 impedance is now close to the limit not only at 3.3 TeV, but also at 50 TeV
- TiN and Carbon coating contribute non-negligible TMCI impedance

Resistive wall of the cold beamscreen, 3.3 TeV, $Z_y^{\text{dip}}$
Collimators: resistive wall

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</tr>
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<tbody>
<tr>
<td>CFC + IM180 (currently baseline)</td>
<td>Inj: -15.6 (x) / -17.0 (y) Top E: -113.4 (x) / -112.8 (y)</td>
<td>Negligible</td>
<td>Inj: 2.36 (x) / 3.76 (y) Top E: 107.0 (x) / 96.7 (y)</td>
<td>Inj: 0.44 Top E: 1.44</td>
</tr>
<tr>
<td>Resistive wall of collimators (including TDI)</td>
<td>MoC + IM180, no coatings</td>
<td>Inj: -25.42 (x) / -27.84 (y) Top E: -153.6 (x) / -148.9 (y)</td>
<td>Negligible</td>
<td>Inj: 0.24 Top E: 0.82</td>
</tr>
<tr>
<td>MoC + IM180, TCSG are coated with Mo</td>
<td>Inj: -25.42 (x) / -27.84 (y) Top E: -153.6 (x) / -148.9 (y)</td>
<td>Negligible</td>
<td>Inj: 0.61 (x) / 0.80 (y) Top E: 29.89 (x) / 26.2 (y)</td>
<td>Inj: 0.16 Top E: 0.58</td>
</tr>
</tbody>
</table>

New:
- Two more material options are added, the previous baseline is beyond the limit and will be reconsidered.
**Collimators: geometrical impedance of the tapers (New)**

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<th>Loss of Landau damping effective impedance, mOhm (definition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical impedance of collimators (including TDI)</td>
<td>Negligible</td>
<td>Non-negligible only if trapped modes are considered</td>
<td>Inj: 1.25 (x) / 0.86 (y)</td>
<td>Inj: 1.04 (Top E: 1.04)</td>
</tr>
<tr>
<td>Allowed total budget</td>
<td>Inj: -1350 Top E: -2050 or -4100 Assuming Nₙ=10¹¹ and number of turns allowed by the feedback n=60 (Inj) and n=600 or 300 (Top E, the value depends on how aggressive the feedback will be)</td>
<td>To be determined based on feedback.</td>
<td>Inj: 12 Top E: 70 Assuming Nb= (safety factor of 3)x10¹¹, RF voltage of 12 MV (Inj) / 32 MV (Top E), Nₙ=0.65 μSacherer</td>
<td>200 Assuming the mechanism of loss of Landau damping as derived by Elena.</td>
</tr>
</tbody>
</table>

- Considerable addition to the broadband collimators impedance unlike in the LHC report (incorrect taper model).
- Stupakov’s formula for flat taper was used and checked with CST.
**Injection kicker (New)**

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<th>TMCI effective impedance, MOhm/m (definition)</th>
<th>Loss of Landau damping effective impedance, mOhm (definition)</th>
</tr>
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<tbody>
<tr>
<td>Aperture 32 x 32 mm (unshielded)</td>
<td>Negligible</td>
<td>Inj: 3.67 (x) / 38.61 (y)</td>
<td>Top E: 5.14 (x) / 45.14 (y)</td>
<td>69.47</td>
</tr>
<tr>
<td>Aperture 48 x 48 mm (unshielded)</td>
<td>Negligible</td>
<td>Inj: 1.63 (x) / 16.76 (y)</td>
<td>Top E: 2.29 (x) / 19.59 (y)</td>
<td>63.08</td>
</tr>
</tbody>
</table>

Allowed total budget

- Inj: -1350
- Top E: -2050 or -4100
- Assuming $N_b=10^{11}$ and number of turns allowed by the feedback $n=60$ (Inj) and $n=600$ or 300 (Top E, the value depends on how aggressive the feedback will be)

To be determined based on feedback.

- Inj: 12
- Top E: 70
- Assuming $N_b=10^{11}$, RF voltage of 12 MV (Inj) / 32 MV (Top E), $N_b=0.65$

200 Assuming the mechanism of loss of Landau damping as derived by Elena.

**Graph:** MKI resistive wall impedance (48 mm, unshielded), 3.3 TeV, $Z_{y_0}$

First order estimate without ferrite shielding – unacceptable. Shielding is necessary.
400 MHz RF cavities** (New)

First order estimate based on LHC cavities. Only two HOMs included. More detailed HOM spectrum is underway (Ivan & Elena).
Crab cavities (New)

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</tr>
</thead>
<tbody>
<tr>
<td>Crab cavities (WOW)</td>
<td>Negligible</td>
<td>Inj: -0.197 (x) / -0.197 (y)</td>
<td>Top E: -3.459 (x) / -3.459 (y)</td>
<td>Inj: 0.03 (x) / 0.03 (y)</td>
</tr>
</tbody>
</table>

Allowed total budget

- Inj: -1350
- Top E: -2050 or -4100
- Assuming \( N_{b} = 10^{11} \) and number of turns allowed by the feedback \( n = 60 \) (Inj) and \( n = 600 \) or 300 (Top E, the value depends on how aggressive the feedback will be)

- To be determined based on feedback.

- Inj: 12
- Top E: 70
- Assuming \( N_{b} \) = (safety factor of \( 3 \times 10^{11} \), RF voltage of 12 MV (Inj) / 32 MV (Top E), \( N_{b} = 0.65 \) \( N_{Sacherer} \)

- 200
- Assuming the mechanism of loss of Landau damping as derived by Elena.

First estimate for WOW cavities by Kai Papke.
Fundamental mode + 6 HOMs included.
Warm beam pipe (see Bernard’s talk)

• Worrying results for 50 TeV settings – high impedance in the drifts of IR A and IR G.
• Analysis at 3.3 TeV is underway.
Conclusions

• The budget is becoming tighter as more elements are added.

• Some options need to be reconsidered:
  • collimator material
  • injection kicker shielding
  • warm pipe

Work to do:
• Better specify the limits for each effective impedance – feedback and Landau damping studies are needed.
• Still many elements to be added:
  • Pumping holes + stiffeners
  • Interconnects
  • BPMs, Y-chambers, bellows