FCC-hh impedance budget and single beam stability

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Part 1: impedance
Main impedance updates since FCC week 2018

• **Tighter beamscreen** aperture is officially accepted
  Vertical aperture: 13.2 mm → 12.22 mm

• The “**stainless steel edge**” issue in the beamscreen is discovered and analyzed (D. Astapovych)

• Measurements of **laser treated surface** impedance are on the way (K. Brunner)

• **Injection kicker magnet** impedance is calculated (A. Chmielinska)

• A high-Q HOM in **crab cavities** is damped
  Dipolar mode at 1.276 GHz: Q-factor 23000 → 1100

• **Collimator impedance** is updated with the new gaps

More details in the next slides
So what is the issue with the stainless steel in the beamscreen?
Stainless steel is \(~1000\) times more resistive than copper:

\[
\rho_{\text{copper}}(50K, 1.06T) = 7.88 \times 10^{-10} \, \Omega m
\]

\[
\rho_{\text{st. steel}} = 6 \times 10^{-7} \, \Omega m
\]
Stainless steel edge (2/3)

Problem: $Z_x$ is increased at single bunch frequencies ($\sim 1$ GHz)
The latest FCC-hh impedance model has similar contributions in $x$ and $y$ from the other elements, leaving no margin for $Z_x$ increase

Similar issue also exists in the LHC beamscreen due to the weld

$$\frac{Z_{\text{with weld}}}{Z_{\text{without weld}}}$$

At kHz level increase in $Z_x^{dip}$ is purely imaginary

Factor of 2.3 increase in $Z_x^{dip}$

Skin depth

<table>
<thead>
<tr>
<th>Skin depth</th>
<th>$f_f$ = $2.1$ kHz</th>
<th>$f_f$ = $1$ GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{copper}}$</td>
<td>$0.3$ mm</td>
<td>$0.4$ $\mu$m</td>
</tr>
<tr>
<td>$\delta_{\text{st. steel}}$</td>
<td>$8.5$ mm</td>
<td>$12$ $\mu$m</td>
</tr>
</tbody>
</table>

From Carlo Zannini’s PhD thesis

$$f_{\text{LHC}} = f_{\text{FCC}}$$

Problem: $Z_x$ is increased at single bunch frequencies ($\sim 1$ GHz)
The latest FCC-hh impedance model has similar contributions in $x$ and $y$ from the other elements, leaving no margin for $Z_x$ increase
**Stainless steel edge (3/3)**

The value in the vertical plane is almost not affected by the issue: $\text{Im}(Z_y) = 12.2 \, \Omega/m^2$ at 1 GHz. We should aim to not exceed this value for $\text{Im}(Z_x)$.

<table>
<thead>
<tr>
<th></th>
<th>$\text{Im}(Z_x)$ per meter [(\Omega/m^2)] at 1 GHz, BI2D result (D. Astapovych)</th>
<th>$\text{Im}(Z_x)$ per meter [(\Omega/m^2)] at 1 GHz, CST - discretized borders</th>
<th>$\text{Im}(Z_x)$ per meter [(\Omega/m^2)] at 1 GHz, CST - borders on mesh diagonals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present geometry, if everything was copper coated</td>
<td>10.86</td>
<td>10.40</td>
<td>11.55</td>
</tr>
<tr>
<td>Present geometry with exposed steel edge</td>
<td>22.45</td>
<td>25.0</td>
<td>36.33</td>
</tr>
<tr>
<td>Steel and copper are cut at 45 deg</td>
<td>18.06</td>
<td>14.83</td>
<td>19.01</td>
</tr>
</tbody>
</table>

Preferred solution: coating of the edge, but other options (bending, sharp cuts) could be considered.
What is the progress on the impedance of a laser-treated surface?
Laser treated surface impedance (1/2)


QPR measurements (cryogenic temperature, no external B-field) show a big difference in impedance depending on the current direction. With the grooves parallel to the beam the results seem OK, but we still need:

- Measurements with B-field
- Measurement of \( \text{Im}(Z_{surf}) \), or at least \( \text{Re}(Z_{surf}) \) in a wide enough frequency span to apply an analytical model.

For the moment, AC coating is assumed in the impedance budget, but can be changed to laser treatment if FRESCA experiments show moderate impedance increase
Laser treated surface impedance (2/2)

Experiment at FRESCA – preparation is ongoing with K. Brunner and S. Calatroni

Recent results from K. Brunner: prototype test-stand allows measuring copper resistivity with 10% accuracy (room temperature, no B-field)

![Graph showing resistivity vs. frequency for internal and external tubes and theoretical resistivity.](chart.png)

Even mode

Odd mode
So what is the MKI impedance?
MKI impedance (1/2)

New shielded design (spiral shielding) vs old unshielded design (32 mm aperture)

The shielding reduces the broadband impedance but introduces resonant peaks at frequencies below 500 MHz

See presentation by A. Chmielinska for details
Problem: If all 18 MKIs were resonantly adding, the CB instability driven by the resonances would be too fast.
Solution: Split 18 magnets in 9 pairs and detune each pair by 1%

Total weighted impedance of 18 MKIs:

**Max peak in**

\[
\text{Max peak in } Re(Z_x) = 125 \text{ M}\Omega/m
\]

Single bunch effective impedance in the horizontal plane

\[
\text{Im}\left(Z_{SB}^{eff}\right) = 1.6 \text{ M}\Omega/m
\]

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**MKI impedance (2/2)**

MKI May 2019, 3p3TeV, \(Z_{zip}'\)

- **Real part**
- **Imaginary part**

Graph showing frequency vs. impedance components.
What is the present state of the impedance model?
Total FCC-hh impedance as of June 2019

- Squeezed collimators
- Magnetoresistance of the beamscreen

Weighted with the local $\beta$-function

Last update: May 2019
Distribution of dipolar impedance by elements

**Frequencies important to single bunch instabilities**

Coupled bunch instability is always dominated by the resistive wall impedance of the beamscreen.

Single bunch instabilities are dominated by:
- At injection: res wall BS, BS coating, collimators, interconnects, MKI
- At top energy: Collimators
## Effective Sacherer impedances

<table>
<thead>
<tr>
<th></th>
<th>Current value at injection</th>
<th>Max allowed at injection</th>
<th>Current value at top energy</th>
<th>Max allowed at top energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\left[ \frac{\text{Im} Z \parallel n}{</td>
<td>n</td>
<td>n} \right]_{\text{Landau}}^{\text{eff}}$</td>
<td>29.3 mΩ</td>
<td>200 mΩ</td>
</tr>
<tr>
<td>$\left[ \text{Re} Z \perp \right]_{\text{CB}}^{\text{eff}}$</td>
<td>-1080 MΩ</td>
<td>-1360 MΩ</td>
<td>-2290 MΩ</td>
<td>-2740 MΩ</td>
</tr>
<tr>
<td>$\left[ \text{Im} Z \perp \right]_{\text{SB}}^{\text{eff}}$</td>
<td>9.9 MΩ</td>
<td>11.6 MΩ</td>
<td>65.4 MΩ</td>
<td>74.0 MΩ</td>
</tr>
</tbody>
</table>

### Definition for the max allowed values:

\[ n_{\text{turns}} = -\frac{8\sqrt{\pi EQ}}{e^2N_b Mc \times \text{Re}(Z_{\text{CB}}^{\text{eff}})} = \begin{cases} 3 \times 20 \text{ turns at injection} \\ 3 \times 150 \text{ turns at top energy} \end{cases} \]

\[ N_b^{\text{th}} = \alpha \frac{4\pi E \tau_b Q_s Q}{e^2 c \times \text{Im}(Z_{\text{SB}}^{\text{eff}})} = 3 \times 10^{11} \]
Part 2: single beam stability*

Done with the previous version of the impedance model, although the difference is marginal (MKI and new collimator gaps)

* For stability with the beam-beam effects, see the talk by Tatiana Pieloni
Simulated stabilization scheme

Landau octupoles

Transverse feedback (damper)

Damper type:
- Bunch by bunch (gain independent of CB number)
- Not high-bandwidth (equal kick to all particles in a bunch)

Phase: resistive

Damping rate at injection:
65 turns $\approx 3 \times 20$ turns

Damping rate at flat top:
460 turns $\approx 3 \times 150$ turns

Stabilizing effect:

\[
\text{max}(\text{Im}(\Delta Q_y)_{\text{stable}}) \propto \left(\beta_{yF}^2 + \beta_{yD}^2\right) \frac{\epsilon_{\text{norm}}}{\gamma^2} \cdot \frac{O_3}{I_{\text{max}}} \frac{L_{\text{oct}} N_{\text{oct}}}{I}
\]

Effectiveness

Strength

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LHC top energy</th>
<th>FCC injection/top energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient $O_3$ / (T/m$^{-3}$)</td>
<td>63100</td>
<td>200 000</td>
</tr>
<tr>
<td>Length $L_{\text{oct}}$ / (m)</td>
<td>0.32</td>
<td>0.5</td>
</tr>
<tr>
<td>Numb. of oct. $N_{\text{oct}}$</td>
<td>168</td>
<td>480</td>
</tr>
<tr>
<td>$\beta_{yD}$ / (m)</td>
<td>175.5</td>
<td>352</td>
</tr>
<tr>
<td>$\beta_{yF}$ / (m)</td>
<td>30.1</td>
<td>64</td>
</tr>
<tr>
<td>Emittance $\epsilon_{\text{norm}}$ / (m)</td>
<td>3.75</td>
<td>2.2</td>
</tr>
<tr>
<td>Max. current $I_{\text{max}}$ / (A)</td>
<td>550</td>
<td>720</td>
</tr>
<tr>
<td>Nominal current $I$ / (A)</td>
<td>500</td>
<td>15 / 720</td>
</tr>
</tbody>
</table>
Results of multi-bunch DELPHI simulation (13068 bunches). Y-plane (most critical). Chromaticity range $0 < Q_p < 20$, 65 turns feedback gain.

Even for the weakest feedback capable of fully suppressing the rigid bunch mode (65 turns), all $|k| \geq 1$ modes lie factor of 4 below the octupoles stability curve.
Stability diagram at top energy

Octupole stability region for $I = 720A$ (scaled from data from C. Tambasco)

Results of multi-bunch DELPHI simulation (13068 bunches). Y-plane (most critical). Chromaticity range $0 < Q_p < 20$, 460 turns feedback gain.

Even for the weakest feedback capable of fully suppressing the rigid bunch mode (460 turns), all $|k| \geq 1$ modes lie factor of 4 below the octupoles stability curve.
**Results of DELPHI simulation (1 bunch). Y-plane (most critical). Chromaticity = 0.**

**TMCI at injection**

**Nominal bunch intensity**

**Destabilizing effect of a resistive damper**

**TMCI happens between modes 0 and –1 at 4.5 \times 10^{11}**

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left: no damper, right: 20 turns damper
TMCI at top energy

Results of DELPHI simulation (1 bunch). Y-plane (most critical). Chromaticity = 0.

TMCI happens between modes 0 and $-1$ at $4.3 \times 10^{11}$.

Destabilizing effect of a resistive damper.

Nominal bunch intensity.
Conclusions

• Increase in impedance due to 12.22 mm beamscreen aperture is accepted
• HOMs in crab cavities are better damped
• Laser treatment of beamscreen is not yet accepted due to the unknown impedance, but active research is going on
• The “stainless steel edge” issue in the beamscreen is investigated and solutions are proposed
• MKI impedance is calculated
• Laser treatment of beamscreen is not yet accepted due to the unknown impedance, but active research is going on
• Number of octupoles is sufficient with a safety margin of more than 3
• Feedback damping rate 20 turns / 150 turns is sufficient at injection / flat top with a safety factor of 3
• Single bunch mode coupling instability threshold is more than 3 times higher than the bunch intensity
Back-up slides
Multibunch TMCI (injection)
Multibunch TMCI (top energy)