Updates on the longitudinal impedance of the LHC V2 goniometer

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Introduction

- The V2 model is the one currently installed in the LHC.
- This model was measured in 2017 and 2019.
- CST EM simulations started in February 2019.
- More information and detailed analysis on the material presented here can be found in the 160-pages report to be published.
Contents

- Description of the model used in simulations
- Positions of holder and crystal in simulations
- Impedance tables from wakefield simulations
- Comparison between simulations and RF measurements
- Evaluation of power-losses
- Conclusions
Description of the model used in simulations

- An accurate CAD model of the V2 goniometer was provided by the EN Department.  
  - It is the model used in simulations, except for the bellows which were simplified.

- Components materials have been characterized.

Piezo-ceramic (conductivity dispersion model $\varepsilon_r=30$, $\sigma_{el}=1e-7$ S/m)

Crystal in silicon (c.d.m. $\varepsilon_r=11.9$, $\sigma_{el}=2.5e-4$ S/m)

Holder in titanium ($\sigma_{el}=5.8e5$ S/m)

Support for mirror and holder in aluminum ($\sigma_{el}=3.6e7$ S/m)

Mirror in glass (c.d.m. $\varepsilon_r=7.5$, $\sigma_{el}=1e-11$ S/m)

Contact in gold ($\sigma_{el}=4.6e7$ S/m)
Four beam-crystal distances were taken into account in simulation:

- 54 mm -> goniometer in parking position for proton-beam operation.
  - Value also considered in the 2017 and 2019 RF measurements.
- 14 mm -> not supposed to be used in operation.
  - This distance was considered in the 2017 and 2019 RF measurements.
- 8 mm and 2 mm, average values for ion-beam operation at bottom and top respectively.
  - These distances were not considered in the 2017 and 2019 RF measurements.

### Beam-crystal distances (mm) in operation for ion beams

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>LHC flat bottom</td>
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<td>1.71</td>
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</table>

### Beam-crystal distances (mm) in simulations
54 mm distance with holder and crystal: numerical convergence

- Mesh-grid parameters:
  - CPW: cells per wavelength;
  - FMC: fraction of maximum cell.

- The differences in $f_r$ are negligible, being less than 1%.

- The discrepancies in $R_s$ are of few, except for modes 3 and 5, where $R_s$ varies by 49% and 33% respectively.
54 mm distance with holder & crystal: modes

Most accurate table

<table>
<thead>
<tr>
<th>Mode</th>
<th>( f_r ) [MHz]</th>
<th>( R_s ) [Ω]</th>
<th>( Q )</th>
<th>( d_l ) [m]</th>
<th>( A_l ) [V/nC]</th>
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</thead>
<tbody>
<tr>
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<td>499</td>
<td>349</td>
<td>490</td>
<td>94</td>
<td>2.2</td>
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<tr>
<td>2</td>
<td>590</td>
<td>27</td>
<td>474</td>
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<td>231</td>
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<td>2.6</td>
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<tr>
<td>5</td>
<td>791</td>
<td>63</td>
<td>378</td>
<td>46</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>835</td>
<td>2289</td>
<td>904</td>
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<td>7</td>
<td>912</td>
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<td>313</td>
<td>33</td>
<td>0.3</td>
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<tr>
<td>8</td>
<td>993</td>
<td>56</td>
<td>278</td>
<td>27</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Mode features

- **16 modes are visible between 500 MHz and 1.46 GHz.**
- **Mode 6 has the highest** \( R_s \), followed by modes 16, 10, 1 and 9.
  - All resonate in the bottom region of the external tank.
- **Mode 6 at 835 MHz has the largest** \( d_l \) (>100 m).
- **Mode 16 at 1429 MHz has the highest** \( A_l \) (> 14 V/nC).
- **Mode 3 at 687 MHz has** \( R_s < 100 \, \Omega \) that increases when the beam-crystal distance reduces.
  - Mostly due to holder and crystal.
14 mm distance with holder and crystal: numerical convergence

- Pairs of corresponding modes are indicated by numbers.

- Sets of modes which cannot be easily matched together are labelled by letters.

- For the numbered modes:
  - The differences in $f_r$ are negligible, being less than 1%.
  - The differences in $R_s$ are relatively high for modes 7 and 10, being respectively of 19% and 54%.

- Numerical convergence is only partially reached, mostly as concerns the A and B sets of modes.
  - However this setup is not operational.
14 mm distance with holder & crystal: modes

**Most accurate table**

![Re Z (Ω) vs Frequency [GHz] graph with modes 1 to 15 labeled]

- **CPW = 16, FMC = 16**

- **Electric-field monitors**

- **Mode features table**

<table>
<thead>
<tr>
<th></th>
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<td>489</td>
<td>94</td>
<td>0.6</td>
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<td>10</td>
<td>1159</td>
<td>843</td>
<td>667</td>
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<td>212</td>
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<td>1203</td>
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<td>1290</td>
<td>93</td>
<td>620</td>
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<td>1.2</td>
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<td>946</td>
<td>579</td>
<td>590</td>
<td>60</td>
<td>5.8</td>
<td>15</td>
<td>1426</td>
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<td>8</td>
<td>1087</td>
<td>452</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **15 modes are visible between 500 MHz and 1.46 GHz.**

- **Mode 4 at 700 MHz** has the highest $R_s$ (>5000 Ω).
  - Mostly due to holder and crystal.
  - It corresponds to the mode at 687 MHz found before.

- **Modes 1, 5, 8, 10 and 15** are located in the bottom region of the tank.
  - Their existences are not affected by the crystal position (correspondences with modes found before).
8 mm distance with holder and crystal: numerical convergence

- Modes 6 and 12, with relatively low $R_s$, are visible only with the most refined grid.

- The discrepancies in $f_r$ are negligible, being at maximum of 1%.

- The differences in $R_s$ are relatively high for modes 8 and 15 (79% and 37%).
  - However for 8 modes out of 16 the differences in $R_s$ are maximum of 5%.

- Numerical convergence is only partially reached, e.g. for modes 8, 15, 6, 12.
  - Problematic to increase grid resolution since computational time > 2 weeks.
8 mm distance with holder & crystal: modes

Most accurate table

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f_r$ [MHz]</th>
<th>$R_s$ [Ω]</th>
<th>$Q$ [1]</th>
<th>$d_1$ [m]</th>
<th>$A_i$ [V/nC]</th>
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<td>404</td>
<td>106</td>
<td>0.05</td>
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<td>491</td>
<td>94</td>
<td>0.2</td>
</tr>
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<td>4</td>
<td>639</td>
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<td>605</td>
<td>90</td>
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<td>74</td>
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<td>767</td>
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<td>99</td>
<td>12</td>
<td>1.1</td>
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<td>836</td>
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<td>69</td>
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<td>1232</td>
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<td>12</td>
<td>1372</td>
<td>111</td>
<td>402</td>
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<td>13</td>
<td>1432</td>
<td>1346</td>
<td>959</td>
<td>64</td>
<td>12.3</td>
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</tbody>
</table>

Electric-field monitors

- 16 modes are visible between 380 MHz and 1.46 GHz.

- Mode 5 at 700 MHz has the highest $R_s$ (>8000 Ω).
  - Mostly due to holder and crystal.
  - It corresponds to the mode at 700 MHz found before.

- Modes 3, 7, 10, 11 and 16 are located in the bottom region of the tank.
  - Their existences are not affected by the crystal position (correspondences with modes found before).

- Also the modes 4, 8, 9, 15 have correspondences with modes found when the beam-crystal distance is 14 mm.
Mode 14, with relatively low $R_s$, is visible only with the most refined grid.

The discrepancies in $f_r$ are in general negligible, being less than 1%.

The differences in $R_s$ are relatively high for modes 8, 9 and 10 (44%, 48% and 30%).

However for 9 modes out of 19 the differences in $R_s$ are maximum of 5%.

Numerical convergence is only partially reached, e.g. for modes 8, 9, 10, 14.

Problematic to increase grid resolution since computational time $> 2$ weeks.
2 mm distance with holder & crystal: modes

- **Most accurate table**

<table>
<thead>
<tr>
<th>Mode</th>
<th>(f_r) [MHz]</th>
<th>(R_s) [(\Omega)]</th>
<th>(Q) [(\text{dB})]</th>
<th>(d_t) [m]</th>
<th>(A_t) [(\text{V/nC})]</th>
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<td>480</td>
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<td>495</td>
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<td>0.05</td>
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<td>106</td>
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<td>340</td>
<td>38</td>
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<td>856</td>
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<td>528</td>
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<td>659</td>
<td>68</td>
<td>10.0</td>
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<td>944</td>
<td>1244</td>
<td>673</td>
<td>68</td>
<td>11.0</td>
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</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>(f_r) [MHz]</th>
<th>(R_s) [(\Omega)]</th>
<th>(Q) [(\text{dB})]</th>
<th>(d_t) [m]</th>
<th>(A_t) [(\text{V/nC})]</th>
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<td>1008</td>
<td>947</td>
<td>63</td>
<td>9.6</td>
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</tbody>
</table>

- **Mode features**

- **Mode 5 (703 MHz)** has the highest \(R_s\) (>14000\(\Omega\)):
  - Mostly due to holder and crystal.
  - Correspondence with the mode at 700 MHz found before.

- **Modes 3, 6, 12, 13 and 19** correspond with the modes found before:
  - Their existences are not affected by the crystal position.
  - Mode 3 is not anymore located in the bottom part of the external tank.

- **Also the modes 4, 9 and 10** correspond to modes found with a beam-crystal distance of 8 mm.
Contents

- Description of the model used in simulations
- Positions of holder and crystal in simulations
- Impedance tables from wakefield simulations
- Comparison between simulations and RF measurements
- Evaluation of power-losses
- Conclusions
Summary of RF measurements results

- Without crystal: with (without) holder in 2017 (2019).
- In table, \( Q \) of corresponding mode in wire measurements is in ( ).
  - Modes found with probe are also found with wire.
- Two general agreements: modes at 835 MHz and 1140 MHz.

### 2017 and 2019 wire measurements

- Without crystal: with (without) holder in 2017 (2019).
- In table, \( Q \) of corresponding mode in wire measurements is in ( ).
  - Modes found with probe are also found with wire.
- Two general agreements: modes at 835 MHz and 1140 MHz.

### 2017 and 2019 probe measurements

<table>
<thead>
<tr>
<th>( f_r ) [MHz]</th>
<th>Without crystal</th>
<th>With crystal</th>
<th>Without crystal</th>
<th>With crystal</th>
</tr>
</thead>
<tbody>
<tr>
<td>410</td>
<td></td>
<td></td>
<td>75 (56 at 401 MHz)</td>
<td></td>
</tr>
<tr>
<td>448</td>
<td></td>
<td></td>
<td>92 (60)</td>
<td></td>
</tr>
<tr>
<td>459</td>
<td>74 (94)</td>
<td></td>
<td>37 [n.d. ( R_s \leq 1 \Omega )]</td>
<td></td>
</tr>
<tr>
<td>481</td>
<td>94 (54)</td>
<td></td>
<td>105 (76)</td>
<td></td>
</tr>
<tr>
<td>480, 483, 481, 479</td>
<td>28 (31)</td>
<td>56 (28 at 474 MHz)</td>
<td>40 (34)</td>
<td>58 (41 at 471 MHz)</td>
</tr>
<tr>
<td>551</td>
<td></td>
<td></td>
<td>27 [n.d. ]</td>
<td></td>
</tr>
<tr>
<td>638, 615</td>
<td>105 (105)</td>
<td></td>
<td>42 (36 at 605 MHz)</td>
<td></td>
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<tr>
<td>672, 687, 672, 690</td>
<td>136 (91)</td>
<td>8 (110 at 672 MHz)</td>
<td>123 (132)</td>
<td>n.d. (88 at 675 MHz)</td>
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<tr>
<td>753</td>
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<td>31 (56)</td>
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<td>837</td>
<td>184 (118)</td>
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<td>202 (96)</td>
<td>377 (220)</td>
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<td>219 (138)</td>
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<td>898</td>
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<td>215 (251)</td>
<td>256 (230)</td>
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<td>1164, 1154, 1170, 1154</td>
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<td>296 (252)</td>
<td>251 (114)</td>
<td>326 (211)</td>
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<tr>
<td>1200</td>
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<td>249 (181)</td>
<td>120 [n.d.]</td>
<td>258 (185)</td>
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<td>87 (163)</td>
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<td>82 (112)</td>
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<tr>
<td>1492</td>
<td>282 (327)</td>
<td></td>
<td>149 (214)</td>
<td></td>
</tr>
</tbody>
</table>
Wire measurements vs simulations: 54 mm distance without holder and crystal

- Generally $R_s$ and $Q$ are larger in simulation.

- Examples of agreement in $f_r$ with 2017 and 2019 wire measurements:
  - Mode 1 (498 MHz);
  - Mode 3 (831 MHz);
  - Mode 4 (912 MHz);
  - Mode 6 (1156 MHz);
  - Mode 10 (1428 MHz).

- Examples of disagreement with 2019 wire measurements:
  - Modes 8 (1356 MHz) and 9 (1401 MHz) do not have correspondences.
Measurements vs simulations: 54 mm distance with holder and crystal

- Generally $R_s$ and $Q$ are larger in simulation.

- Examples of agreement in $f_r$ with 2017 and 2019 wire measurements:
  - Mode 1 (499 MHz);
  - Mode 6 (835 MHz);
  - Mode 10 (1156 MHz);
  - Mode 16 (1429 MHz).

- Examples of disagreement with 2019 measurements:
  - Modes 4 (782 MHz), 5 (791 MHz) and 9 (1086 MHz) do not have correspondences.
Measurements vs simulations: 14 mm distance without holder and crystal

- Generally $R_s$ and $Q$ are larger in simulation.

- Examples of agreement in $f_r$ with 2017 and 2019 wire measurements:
  - Mode 1 (498 MHz);
  - Mode 3 (832 MHz);
  - Mode 8 (1155 MHz);
  - Mode 12 (1427 MHz).

- Examples of disagreement with 2019 measurements:
  - Modes 5 (1041 MHz) and 7 (1110 MHz) do not have correspondences.
Measurements vs simulations: 14 mm distance with holder and crystal

- Generally $R_s$ and $Q$ are larger in simulation.
- Examples of agreement in $f_r$ with 2017 and 2019 wire measurements:
  - Mode 2 (609 MHz);
  - Mode 3 (645 MHz);
  - Mode 5 (833 MHz);
  - Mode 7 (946 MHz);
  - Mode 10 (1159 MHz).
- Examples of disagreement with 2019 measurements:
  - Modes 4 (701 MHz), 8 (1087 MHz) and 9 (1119 MHz) do not have correspondences.
Evaluation of power losses: intro

- Power lost by a beam inside a resonating device:

\[
P = f_0 q^2 N_{beam} \int_{-\infty}^{\infty} df |\Lambda(f)|^2 \text{Re}[Z(f)]
\] (1)

- In the LHC and considering the goniometer:
  - \( T_0 = 1/f_0 \approx 86 \ \mu s \)
  - \( q = e \) (protons) or \( q = 82e \) (lead ions)
  - \( N_{beam} \) and \( \Lambda \) depend on the considered beam
  - \( Z \) depends on the goniometer configuration

- Beam power-spectrum: \( |\Lambda|^2 \)
Studied LHC beams (1/2)

Four types of LHC are considered:
- Three proton beams and one ion beam.
- For each beam, the measured line-density is numerically reproduced.
  - Flat-top case -> worst case scenario.
- All the bunches are supposed to have a Gaussian distribution -> worst case.
- It was not possible to find filling-pattern data for HiLumi ion beams:
  - Only a worst-case power-loss estimation will be given.

1. Proton beam Fill5979:
- Used in 2017.
- 2556 bunches with bunch intensity $N_b = 1.1 \times 10^{11}$ ppb (particles per bunch).
- $N_{beam} = 2.81 \times 10^{14}$ protons.
- The power spectrum becomes relatively small after 1.5 GHz.
Studied LHC beams (2/2)

2. Proton beam HL2760b:
   - HiLumi beam.
   - 2760 bunches with \( N_b = 2.3 \times 10^{11} \) ppb and \( \sigma_{bunch} = 1.2 \) ns.
   - \( N_{beam} = 6.35 \times 10^{14} \) protons.

3. Proton beam 8b4eHL (8 bunches 4 empty buckets):
   - HiLumi beam used for electron cloud mitigation.
   - 1972 bunches with \( N_b = 2.3 \times 10^{11} \) ppb.
   - \( N_{beam} = 4.54 \times 10^{14} \) protons.

   ![Line density and Power spectrum graphs]

   - The side bands around the main power-spectrum lines are due to the peculiar filling pattern.

4. Ion beam:
   - Used in the last part of the 2018 run (from fill 7467).
   - 75 ns scheme adopted: each batch composed of 3 bunches separated by 3 buckets.
   - 733 bunches with \( N_b = 2.1 \times 10^8 \) ppb and \( \sigma_{bunch} = 0.275 \) ns at the fill start.
   - \( N_{beam} = 1.26 \times 10^{13} \) protons.
Goniometer supposed to be not operational for proton beams:
- Impedance related to the 54 mm beam-crystal distance (parked out setup):

Three ways to evaluate the dissipated power:
- Direct power-computation using the power formula (1). Inaccurate since:
  • Power spectrum changes with time due to bunch oscillations.
  • Shifts in $f_r$ and $R_s$ could occur when the mesh resolution is increased in simulation, since numerical convergence isn’t entirely reached.
- Average (maximum) power using perturbative analysis:
  • $Z$ is shifted within plus or minus 20 MHz on 200 frequency points,
  • The corresponding power losses are computed using (1),
  • The average (maximum) of these values are considered.

![Graph showing frequency and impedance](image-url)
Power losses for proton beams (2/3)

- The power values are:

<table>
<thead>
<tr>
<th>Type of LHC beam</th>
<th>Impedance table (beam-crystal distance)</th>
<th>Direct power computation</th>
<th>Average power using perturbative analysis</th>
<th>Maximum power using perturbative analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill5979</td>
<td>54 mm</td>
<td>4.08 W</td>
<td>23.54 W</td>
<td>195.29 W</td>
</tr>
<tr>
<td>HL2760b</td>
<td>54 mm</td>
<td>10.57 W</td>
<td>76.84 W</td>
<td>595.12 W</td>
</tr>
<tr>
<td>8b4eHL</td>
<td>54 mm</td>
<td>21.11 W</td>
<td>52.56 W</td>
<td>305.15 W</td>
</tr>
</tbody>
</table>

- The direct computation provides lower values than the ones obtained with the perturbative analysis:
  - Too optimistic values due to casual little overlapping of modes and power-spectrum main lines.

- The HiLumi beams lead to more dissipated power:
  - Mostly due to the higher number of protons, for instance:
    - $\frac{N_{HL2760b}^LHC}{N_{beam}^{Fill5979}} = 2.26$, $\frac{P_{HL2760b}^{dir}}{P_{Fill5979}^{dir}} = 2.59$, $\frac{P_{HL2760b}^{avg}}{P_{Fill5979}^{avg}} = 3.26$, $\frac{P_{HL2760b}^{max}}{P_{Fill5979}^{max}} = 3.05$
The power-loss density reveals the modes contributing the most to the power-loss:

\[ P_d(f) = f_0 q^2 N_{beam}^2 |\Lambda(f)|^2 \text{Re}[Z(f)] \]

Power-loss densities providing the average and maximum power values:

- Modes 1 (499 MHz) and 6 (835 MHz) give the largest contributions:
  - Both modes mostly resonates close to the replacement chamber.
Power losses for ion beams (1/2)

- Goniometer supposed to be operational for ion beams:
  - Impedances related to the 8 mm and 2 mm beam-crystal distances:
    - 8 mm, LHC flat bottom
    - 2 mm, LHC flat top

- The direct computation provides lower values than the ones obtained with the perturbative analysis.

- The values at flat top are higher than the ones at flat bottom:
  - Mostly due to the mode 5 (700 MHz) having higher $R_s$ at 2 mm distance:
    \[ \frac{R_s^{2\text{mm}}}{R_s^{8\text{mm}}} = 1.73, \frac{P_{\text{avg}}^{\text{top}}}{P_{\text{avg}}^{\text{bot}}} = 1.52 \]

- Losses for protons are generally higher than the ones for ions by 2 orders of magnitude:
  - Mostly due to the lower number of protons in the ion beams, for instance
    \[ \frac{N_{\text{beam}}^{\text{HL2760b}}}{N_{\text{beam}}^{\text{ion}}} = 50.40, \frac{P_{\text{dir}}^{\text{HL2760b}}}{P_{\text{dir}}^{\text{ion, top}}} = 40.65 \]

Power evaluated using the same methods adopted for protons:
Power losses for ion beams (2/2)

- Power-loss densities providing the average and maximum power values:
  - Mode 5 (700 MHz) gives the largest contributions:
    - Both at flat bottom and top, this mode mostly resonates close to the holder and crystal.

- Due to the lack of reliable data on the filling schemes of HiLumi ion beams, power values could not be computed.
  - According to a worst-case estimation, the power-loss will be at maximum 5 W.
Conclusions

- Updates on the longitudinal impedance tables have been provided together with analysis of the resonating modes.
  - Four crystal-beam distances were considered and an understanding of how these distances affect the different modes was gained.
  - Numerical convergence not reached for relatively few modes.

- Simulations have been compared with 2017 and 2019 RF measurements.
  - In general higher $Q$ and $R_s$ values in simulations.
  - Partial agreement in $f_r$.

- Power-losses have been provided for proton and ion beams.
  - Perturbative analysis was performed to take into account variations in impedance and beam power-spectrum.
  - Power-loss densities reveal the modes which contribute the more to the dissipated power.