Characterization of the longitudinal impedance of the LHC UA9 goniometer through RF measurements and simulations

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Acknowledgements:
Introduction

In the last week of June 2019, new RF measurements were performed to characterize the longitudinal impedance of one of the LHC goniometers. This gonio
- is horizontal, mounts a quasi-mosaic crystal and was removed from the LHC in 2018;
- was also used in the previous 2017 measurements.
  - A vertical gonio with similar design but without crystal was also measured in 2017.

Four reasons motivated these new RF measurements:
- Significant discrepancies between 2017 measurements and CST simulations.
  - Discrepancies also due to the simulations themselves: often too simplified models were used and the models didn’t correspond to the measured goniometers.
- Some discrepancies and anomalies in 2017 measurements.
- It was possible and it made sense to perform a check of the 2017 measurements.
  - The gonio, very complex in structure, was available for new measurements.
- Possibility to compare 2017 and 2019 measurements with new CST simulations.
  - In 2019 the CAD model of this measured gonio was available for the first time.

In this talk:
- the 2017 measurements are compared with the 2019 measurements,
- new simulations are compared with 2017 and 2019 measurements,
- first estimates for power losses are given for realistic present and future LHC scenarios.
Contents

- Introduction.

- Goniometer version V2 and corresponding CAD model:
  - Manipulations on the CAD and dimensions of some important components.
  - Material characterization of some significant components.
  - Positions of holder and crystal in bench measurements and LHC operation.

- RF measurements for the longitudinal impedance of the V2 goniometer:
  - Overview of the most significant 2017 measurements, holder parked out and 40 mm in.
  - Overview of the most significant 2019 measurements, holder parked out and 40 mm in.
  - Comparison between 2017 and 2019 measurements.

- Wakefield simulations for the V2 goniometer:
  - Holder parked out and 40 mm in.

- Comparison between RF measurements and simulations for the V2 goniometer:
  - Holder parked out and 40 mm in.

- Simulations of realistic LHC scenarios and computations of dissipated power with the V2 goniometer:
  - Holder parked out for protons.
  - Holder parked 46 mm and 52 mm in for ions respectively at LHC flat bottom and top.
  - Holder parked 46 mm and 52 mm in for protons respectively at LHC flat bottom and top.

- Conclusions.
Available goniometer CADs

- Three different CADs have been available along the years, from 2014 to 2019.
  - Significant differences between the three versions, both externally and internally.
  - CAD V2 corresponds to the goniometer measured in 2017 and 2019.

**CAD V1, strip crystal (2014 version)**

**CAD V2, quasi-mosaic crystal (installed during EYETS 2016/2017)**

**CAD V3, quasi-mosaic crystal (new model, not yet produced)**
CAD V2 was simplified outside the tank without therefore affecting the simulation results.

- Then the two bellows connected to the corresponding motors were replaced by cylinders. These replacements in practice don’t affect the simulation results.

- Then a parametric model was built able to:
  - horizontally translate mechanical stage, holder and crystal to an arbitrary position,
  - vertically translate the auxiliary beam pipe to an arbitrary position.

**Diagram 1:**
- CAD V2 simplified outside the tank
- Frontal view

**Diagram 2:**
- Cutting plane along z direction (holder and crystal parked out, auxiliary beam pipe parked out)
- Simplified bellows

**Diagram 3:**
- Zoom on the holder and crystal

**Dimensions:**
- 250 x 225 x 205
- 79 x 111 x 64
- 81 x 93 x 54
- 40 x 40 x 30
- 25 x 23 x 7
- 4 x 4 x 25
Materials of the most significant components have been characterized.

All components in gray are made of stainless steel with electric conductivity $\sigma_{el}=1.3e6 \text{ S/m}$.

Piezo-ceramic with $\varepsilon_r=30$, $\sigma_{el}=1e-7 \text{ S/m}$.

Crystal in silicon with $\varepsilon_r=11.9$, $\sigma_{el}=2.5e-4 \text{ S/m}$.

Holder in titanium (alloy Ti6Al4V grade 5) with $\sigma_{el}=5.8e5 \text{ S/m}$.

Support for mirror and holder, in aluminum with $\sigma_{el}=3.6e7 \text{ S/m}$.

Mirror in glass with $\varepsilon_r=7.5$ and $\sigma_{el}=1e-11 \text{ S/m}$.

Contact in gold with $\sigma_{el}=4.6e7 \text{ S/m}$.
CAD V2: positions for holder and crystal in measurements

- The distance between the crystal and the beam is calculated as the distance between the beam pipe central axis and the face of the crystal closer to that axis.

- **Most considered distances in 2017 and 2019 measurements:**
  - 54 mm, corresponding to a parked-out goniometer.
  - 14 mm.

- In 2019 measurements also the intermediate distance 34 mm was taken into account.

- However, to avoid with some safety margin possible collisions between the crystal and the wire used for the RF measurements, the minimum distance measured was 14 mm.
  - Few exceptions with distance 4 mm during probe measurements.
LHC operation with protons: goniometer parked out (54 mm distance).

LHC operation with ions: the distances were provided by M. D’Andrea:

- Current situation: 2 gonios per ring, one horizontal (ST crystal) and one vertical (QM crystal).
- Possible future scenario: 4 gonios per ring, two horizontals and two verticals, so that each transverse side of the beam-pipe will contain one gonio.
- Note: the horizontal gonio with QM crystal measured in 2017 and 2019 is an old B2H removed from the LHC during the Technical Stop in 2018 and replaced by a B2H with ST crystal.
- In simulations the average values for flat bottom and flat top have been considered:
  - 8 mm, flat bottom,
  - 2 mm, flat top.

### CAD V2: positions for holder and crystal in operation

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<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat bottom</td>
<td>9.03</td>
<td>8.15</td>
<td>6.89</td>
<td>8.16</td>
<td>6.93</td>
<td>7.42</td>
<td>8.97</td>
<td>7.54</td>
</tr>
<tr>
<td>Flat top</td>
<td>2.08</td>
<td>1.88</td>
<td>1.59</td>
<td>1.88</td>
<td>1.60</td>
<td>1.71</td>
<td>2.07</td>
<td>1.74</td>
</tr>
</tbody>
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2017 RF wire-measurements on goniometer V2: setup

- The horizontal and vertical goniometers were measured with and without crystals respectively.
- Sum of VNA and resistor impedances not equal to $Z_c$ of beam pipe (diameter 80 mm).
  - Reflection effects seen in measurements.
- CuBe wire with diameter 0.5 mm.
- Both the log formula $Z_{\text{log}}$ and the improved log formula $Z_{\text{LOG}}$ were used to convert $S_{21}^{\text{DUT}}$ to longitudinal impedance.
  - $S_{21}^{\text{REF}}$ was measured aligning the replacement chamber with the beam pipe.
  - Using this measured $S_{21}^{\text{REF}}$ allowed an efficient removal of the reflection effects.

Log formula

$$Z_{\text{log}} = -2Z_c \ln \left( \frac{S_{21}^{\text{DUT}}}{S_{21}^{\text{REF}}} \right)$$

Improved log formula

$$Z_{\text{LOG}} = -Z_c \ln \left( \frac{S_{21}^{\text{DUT}}}{S_{21}^{\text{REF}}} \right) \left[ 1 + \frac{\ln (S_{21}^{\text{DUT}})}{\ln (S_{21}^{\text{REF}})} \right]$$

Characteristic impedance of beam pipe with wire

$$Z_c = \frac{Z_{\text{vac}}}{2\pi} \ln \left( \frac{b}{a} \right) = 304.3 \, \Omega$$
2017 RF wire-measurements on goniometer V2: results

Gonio parked out
Without crystal
With crystal

Improved log formula

Gonio parked
40 mm in
Without crystal
With crystal

Improved log formula

17 modes
14 modes
17 modes
18 modes
1. 2019 measurements confirmed the anomaly found in 2017 about the modes at 370 MHz: they are due to flange contacts (see e.g. Impedance Meeting of 12/07/2019).

2. The modes at 840 MHz and 1.150 GHz are present in all the four tables.
   - Adding the crystal (dielectric) $f_r$ slightly decreases (Slater theorem) while $R_s$ significantly increases.
3. When the gonio is parked 40 mm in, two modes at 446 MHz and 483 MHz without crystal seem to shift upward in frequency respectively at 606 MHz and 644 MHz.

4. These bumps (magenta) with wave-lengths of 300 MHz seem due to reflections not filtered out. Possible reason:
   - Reference taken with gonio parked out, maybe with different measurements conditions.
2017 RF wire-measurements on goniometer V2: another anomaly

- $S_{21}^{REF}$ was taken for difference positions of the replacement chamber, from 0 mm (aligned with the beam-pipe) to 12 mm out (93 mm out corresponds to parked out).
  - The gonio was always parked out.

- The two sets of modes visible in $S_{21}^{REF}$ with positions above 6 mm resemble the two sets of modes visible only in the impedance table with gonio parked 40 mm in.
2017 probe-measurements on goniometer V2

- Probe-measurements results, only the $f_r$ are compared with wire-measurements, not the Q:
  - Example of matches calculation for gonio parked out without crystal: 4 matches, 5 modes in probe measurements, 9 modes in wire measurements (slide 11) -> average matches = 4,5,9 -> 4/7.

<table>
<thead>
<tr>
<th>$f_r$ [MHz]</th>
<th>Q (gonio parked out)</th>
<th>Q (gonio parked 40 mm in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No crystal</td>
<td>With crystal</td>
</tr>
<tr>
<td>410.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>447.93</td>
<td></td>
<td>91.54</td>
</tr>
<tr>
<td>458.59</td>
<td>74.40</td>
<td></td>
</tr>
<tr>
<td>480.70</td>
<td>94.54</td>
<td>105.0</td>
</tr>
<tr>
<td>551.09</td>
<td>26.68</td>
<td></td>
</tr>
<tr>
<td>638.02/614.80</td>
<td>105.14</td>
<td></td>
</tr>
<tr>
<td>753.45</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>836.87</td>
<td>183.87</td>
<td>200.44</td>
</tr>
<tr>
<td>898.36</td>
<td>77.54</td>
<td>121.56</td>
</tr>
<tr>
<td>1164.36/1153.70/1170.01/1153.70</td>
<td>194.24</td>
<td>295.71</td>
</tr>
<tr>
<td>1377.66</td>
<td></td>
<td>73.59</td>
</tr>
<tr>
<td>1402.76/1400.87</td>
<td>280.75</td>
<td></td>
</tr>
<tr>
<td>1420.32</td>
<td></td>
<td>44.39</td>
</tr>
<tr>
<td>1473.02</td>
<td>86.82</td>
<td>81.72</td>
</tr>
<tr>
<td>1597.47</td>
<td>282.34</td>
<td></td>
</tr>
</tbody>
</table>

- Matches with wire measurements:
  - 4,5,17 -> 4/11
  - 6,6,14 -> 3/5
  - 9,10,17 -> 2/3
  - 7,7,18 -> 14/25

- Global average matching of 23/44 = 52% with important discrepancies, e.g.:
  - the anomaly at 367 MHz when crystal is parked out doesn’t appear in probe measurements;
  - the anomaly at 644 MHz when crystal is parked 40 mm in doesn’t appear in probe measurements.

(1) Considered OK, but 2.5% difference in $f_r$ with wire measurement.
(2) Considered OK, but 1.3% difference in $f_r$ with wire measurement.
The horizontal goniometer was measured with and without crystal.

- Differently from 2017, when the crystal was removed, also the holder was extracted.
  - The gonio was activated and it was faster and easier to remove the two pieces together.

Sum of VNA and resistor impedances not equal to $Z_c = 304 \, \Omega$ of the beam pipe.

- Reflection effects seen in measurements.

Due to lack of time and gonio activation, $S_{21}^{REF}$ was not measured.

CuBe wire with diameter 0.5 mm.

Both the log formula $Z_{\log}$ and the improved log formula $Z_{LOG}$ were used to convert $S_{21}^{DUT}$ to longitudinal impedance.

- $S_{21}^{REF}$ was artificially computed in such a way to remove the reflection effects (see next slides).
2019 RF wire-measurements on goniometer V2: gonio parked out without holder and crystal (1/2)

- Reflection effects were removed in three steps:
  1. Removing the modes from the measured $|S_{21}^{\text{DUT}}|$.
  2. Replacing the modes with polynomial fits, mode after mode, obtaining $|S_{21}^{\text{REF}}|$.
  3. Subtracting $|S_{21}^{\text{REF}}|$ in dB from the measured $|S_{21}^{\text{DUT}}|$ in dB.

- The shape of $|S_{21}^{\text{REF}}|$ can be only roughly guessed, therefore all the fits have a degree of arbitrariness that in fact should not exist.

- Some modes of $|S_{21}^{\text{DUT}}|$ aren’t symmetric with respect to $f_r$:
  - these asymmetries translate in asymmetries in $Z$.

- The measured phase of $S_{21}$ was not corrected in first approximation.

![Construction of $|S_{21}^{\text{REF}}|$](image1.png)  

$|S_{21}^{\text{DUT}}| - |S_{21}^{\text{REF}}|$ and phase of $S_{21}^{\text{DUT}}$
Log and improved log formulae give almost superimposed curves (max diff $\text{Re } Z = 5\%$ at $837 \text{ MHz}$).

- If the phase of $S_{21}^{\text{DUT}}$ is also corrected multiplying it by $e^{2\pi f \frac{L}{c} j}$, where $L = 400 \text{ mm}$ is the distance between the flanges, and
- if in the log and improved log formulae $S_{21}^{\text{REF}} = e^{-2\pi f \frac{L}{c} j}$ is used, then

Log and improved log formulae give almost superimposed curves (max diff $\text{Re } Z = 5\%$ at $837 \text{ MHz}$).

Reflection effects still visible in $\text{Im } Z$.

The value for $L$ was confirmed from the effect of the reflections in the measured $S_{21}^{\text{DUT}}$:

$$2L = \frac{c}{\Delta f} = 798 \text{ mm} \quad \Rightarrow \quad L \approx 400 \text{ mm}$$
2019 wire-measurements on gonio V2: other cases

- The same procedure is applied for the other cases. **Gonio parked out with crystal and holder:**

  - **Construction of $|S^{REF}_{21}|$**
  - **$|S^{DUT}_{21}|$**
  - **$|S^{REF}_{21}|$**
  - **Points used for the fits**
  - This fit doesn’t follow the expected baseline

- **Gonio parked 40 mm in without crystal and holder:**

- **Gonio parked 40 mm in with crystal and holder:**

- **Real part of $Z$**
  - Log formula
  - Improved log formula

  - **$|S^{DUT}_{21}| - |S^{REF}_{21}|$**
  - **Phase of $S^{DUT}_{21}$**
  - **Points used for the fits**
  - This fit doesn’t follow the expected baseline
2019 RF wire-measurements on goniometer V2: results

Gonio parked out
Without holder and crystal
With holder and crystal

Gonio parked 40 mm in
Without holder and crystal
With holder and crystal
2019 RF wire-measurements on goniometer V2: analysis (1/3)

1. Modes at 475 MHz are visible in all cases, \( f_r \) and \( R_s \) decrease adding crystal and holder.

2. When the goniio is parked out, the mode at 670 MHz decreases in \( R_s \) by factor 3. When the goniio is parked 40 mm in, the mode at 670 MHz increases in \( R_s \) by factor 3.
3. Modes at 840 MHz are visible in all cases, $R_s$ decreases adding crystal/holder and also going from gonio parked out to 40 mm in.

4. Modes at 940 MHz and 990 MHz are visible in all cases. $R_s$ increases by less than factor 2 when the gonio is parked out without crystal, and from factor 4 to 10 for the other cases.
5. Modes at 1.14 GHz and 1.20 GHz are visible in all cases. When the gonio is parked 40 mm in, removing the crystal splits the mode at 1.20 GHz into two modes with lower $R_s$. For the other three cases $R_s$ decreases adding the crystal by at least factor 2.

6. Modes at 1.41 GHz, 1.46 GHz and 1.48 GHz are visible in all cases. $R_s$ lowers with the crystal and also going from gonio parked out to 40 mm in.
2019 probe-measurements on goniometer V2

Probe-measurements results, only the $f_r$ are compared with wire-measurements, not the Q:

> Example of matches calculation for gonio parked out without crystal and holder: 8 matches, 8 modes in probe measurements, 10 modes in wire measurements (slide 20) -> average matches = 8,8,10 -> 8/9.

<table>
<thead>
<tr>
<th>$f_r$ [MHz]</th>
<th>Q (gonio parked out)</th>
<th>Q (gonio parked 40 mm in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without holder and crystal</td>
<td>With holder and crystal</td>
</tr>
<tr>
<td>482</td>
<td>28</td>
<td>56 (1)</td>
</tr>
<tr>
<td>673</td>
<td>136</td>
<td></td>
</tr>
<tr>
<td>696</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>838</td>
<td>388</td>
<td>465</td>
</tr>
<tr>
<td>941</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>993</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>1139</td>
<td>279</td>
<td>158</td>
</tr>
<tr>
<td>1200</td>
<td>230</td>
<td>249</td>
</tr>
<tr>
<td>1407</td>
<td>267</td>
<td></td>
</tr>
<tr>
<td>Matches with wire measurements</td>
<td>8,8,10 -&gt; 8/9</td>
<td>4,5,11 -&gt; 1/2</td>
</tr>
</tbody>
</table>

(1) Considered OK but discrepancy in $f_r$ of 1.5% with wire measurements.
(2) Considered OK but discrepancy in $f_r$ of 2.3% with wire measurements.

Global average matching of $33/49 = 63\%$ with important discrepancies mostly when holder and crystals are present, for example:

> the modes at 940 MHz and 990 MHz are visible only in wire measurements;
> the modes at 1.41 GHz, 1.46 GHz and 1.48 GHz are visible only in wire measurements.

The agreement in 2019 is better than the one of 52% found in 2017 (slide 15).
1. As suggested by the found anomalies, the modes at 367 MHz were observed only in 2017.

2. As suggested by the anomaly found during the reference measurements (slide 14), the two modes very close in $f_T$ with the gonio parked in were not observed in 2019.

3. Mode at 830 MHz: when the gonio doesn’t mount the crystal, $R_s$ increases in 2019. When the gonio mounts the crystal, $R_s$ decreases in 2019.
4. For all the four cases, the modes found at 1.15 GHz in 2017 seem to split in two (or three) modes with lower $R_s$ in 2019.

5. The modes found in 2019 at 940 MHz and 990 MHz either are shifted in frequency or not visible in 2017.

6. The mode found at 475 MHz for the four cases in 2019 matches perfectly with 2017 only when the gonio is parked out without crystal.
2017 vs 2019 wire-measurements (3/3)

- 2017 and 2019 RF wire-measurements are compared for the four considered cases:

1. The modes at 1.41 GHz, 1.46 GHz and 1.48 GHz found in 2019 shift in $f_r$ and have a lower $R_s$ in 2017.
2. The modes at 1.077 GHz seen in 2017 are not visible in 2019.
3. The modes at 900 MHz seen in 2017 without crystal are not visible in 2019.
4. The bumps seen in 2017, due likely to residual reflections not filtered out, are not visible in 2019.
5. The mode at 636 MHz seen in 2017 shifts in $f_r$ by more than 5% and decreases in $R_s$ by 175% in 2019.
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- Conclusions.
Wakefield simulations with CAD V2 model: holder parked out with crystal

- In order to validate the RF measurements, the original CAD V2 (with ‘safe’ simplifications, see slide 5) was used to perform wakefield simulations:
  - The complexity of this model doesn’t allow other types of simulations.
  - The choice for this complex model as a reference is due to the difficulty to simplify the CAD model without changing the resonant modes (see IWG of 10/05/2019).

- Assumptions in simulations:
  - The materials of some important components are characterized (slide 6).
  - Vacuum as background material (impossibility in use the vacuum itself as component).
  - 500 m of wavelength to see enough wake decay (see next slide).
  - Max frequency simulated \( f_{\text{max}} = 1.365 \, \text{GHz} \rightarrow \lambda_{\text{min}} = \frac{c}{f_{\text{max}}} = 22 \, \text{cm} \).
  - Cells per minimum wavelength CMW=10, fraction of maximum cell equal to 15, mesh smoothing with equilibrate ratio equal to 1.5.
    - Smallest cell edge 1.33 mm, largest cell edge 9 mm.

- Simulation taken as reference:
  - holder parked out with crystal;
  - model and assumptions mentioned above.
Wake-potential decay in the reference simulation

- Wakelength = 500 m gives a decay of 0.32%.
- The excitation is a Gaussian bunch with $\sigma_{\text{rms}} = 75$ mm corresponding to a maximum beam frequency of 1.365 GHz at -20 dB in power.

\[ W(s) / \text{V/nC} \]

\[ s / \text{mm} \]

\[ 0.02 \]
\[ 0.015 \]
\[ 0.01 \]
\[ 0.005 \]
\[ 0 \]
\[ -0.005 \]
\[ -0.01 \]
\[ -0.015 \]
\[ -0.02 \]

\[ 19 \text{ V/nC} \]

\[ 0.06 \text{ V/nC} \]
(0.32% of peak value)
First consistency checks on the reference simulation

- Different consistency checks are performed on the reference simulation to test the reliability of the obtained results:
  - **10CMW**: reference simulation.
  - **10CMW_externalMargins**: reference simulation with a margin of 2 mm left between the goniometer and the bounding box to avoid conflicts between surface materials.
  - **10CMW_longBeamPipe**: each of the two 79-mm-long pieces of beam-pipe in the reference simulation is extended to 278 mm to test the reliability of the PML boundary conditions along the longitudinal direction.
  - **10CMW_noMaterials**: reference simulation without material characterization: all the goniometer components are in stainless steel, except for the crystal in silicon.
Simulation results for the first consistency checks

In general negligible differences except for modes 5 and 6 when materials are not characterized.

Less than 1% differences in $f_r$ and $R_s$.

$R_s$ reduced by 2 only for the red curve. Less than 1% differences in $f_r$.

$f_r$=651 MHz  $f_r$=730 MHz
Second consistency check on the reference simulation: from with crystal and holder to without

- Indication 1: modes 1, 2, 3, and partially 4, are not due to crystal and holder.
- Indication 2: modes 5 and 6 are due to the holder (the crystal makes $f_r$ decrease and $R_s$ increase).
Third consistency check on the reference simulation: from ‘transmission line’ to ‘analytic’ injection scheme

- The current injection scheme is changed from ‘transmission line’ to ‘analytic’.

- Grid not homogeneous in the z direction, the ‘transmission line’ method gives unwanted reflections:
  - These simulation results show that it is not an issue.

- Note: wake integration method can’t be ‘indirect testbeams or interfaces’ due to gonio asymmetries.
Animations of $|E|$ for the reference simulation (holder parked out with crystal, CMW=10)

(1) $f_r=0.492$ GHz
(2) $f_r=0.820$ GHz
(3) $f_r=1.077$ GHz
(4) $f_r=1.152$ GHz
(5) $f_r=0.651$ GHz
(6) $f_r=0.730$ GHz

- The indications given in slide 33 were correct.
- Modes (5) and (6) have practically the same $|E|$. 

Piston and auxiliary beam pipe

Holder/crystal and mechanical stage

Auxiliary beam pipe and piston

Holder/crystal and mechanical stage
Fourth consistency check on the reference simulation: from 10 CMW to 15 CMW

- For all modes $f_r$ shifts upwards using 15 CMW (negligible except for modes 5 and 6).
- $R_s$ decreases for modes 1, 2, 3, 4 (max 17%), while increases for modes 5 and 6 of 47% and 91%.
- Increasing CMW to 20 for convergence studies requires almost a month of simulation time.
Animations of $|E|$ for the reference simulation changing CMW to 15

- $(1) f_r = 0.496 \text{ GHz}$
- $(2) f_r = 0.827 \text{ GHz}$
- $(3) f_r = 1.083 \text{ GHz}$
- $(4) f_r = 1.155 \text{ GHz}$
- $(5) f_r = 0.705 \text{ GHz}$
- $(6) f_r = 0.788 \text{ GHz}$

- As expected from slide 36, $|E|$ of (1), (2), (3), (4) aren’t significantly affected when CMW is 15 (slide 35).
- 50 MHz shift doesn’t affect (5) since 705 MHz is in a region where $|E|$ seems not to change (slide 35).
- 60 MHz shift affects (6) since 788 MHz is out of the region where $|E|$ seems not to change (slide 35).
Wakefield simulations with CAD V2 model: holder parked 40 mm in with crystal

- The gonio in the reference simulation is moved 40 mm in. Comparison between 10 CMW and 15 CMW:
  - Using 15 CMW $R_s$ decreases, except for the modes (4) and (12), while $f_r$ increases for 4 pairs of modes.
  - Mode (2) splits into the modes (9) and (10), while $R_s$ decreases by 126%.
Animations of $|E|$, holder parked 40 mm in with crystal (CMW=15)

(8) $f_r=0.494$ GHz
(9) $f_r=0.645$ GHz
(10) $f_r=0.653$ GHz
(11) $f_r=0.706$ GHz
(12) $f_r=0.829$ GHz
(13) $f_r=0.965$ GHz
(14) $f_r=1.085$ GHz
(15) $f_r=1.157$ GHz

- Modes (8), (11), (12), (14), (15) can be paired respectively to modes (1), (5), (2), (3), (4) of slide 37.
  - $|E|$ of modes (11) and (5) differ by 18 dB (or equivalently $R_s$ of (11) is 90 times larger, slide 38).
- Modes (9) and (10) are close in $f_r$ and their $|E|$ is mostly localized on the spring under the stage.
- $|E|$ of mode (13) is localized mostly on the aluminum component supporting the holder and the mirror.
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- RF measurements for the longitudinal impedance of the V2 goniometer:
  - Overview of the most significant 2017 measurements, holder parked out and 40 mm in.
  - Overview of the most significant 2019 measurements, holder parked out and 40 mm in.
  - Comparison between 2017 and 2019 measurements.

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- Simulations of realistic LHC scenarios and computations of dissipated power with the V2 goniometer:
  - Holder parked out for protons.
  - Holder parked 46 mm and 52 mm in for ions respectively at LHC flat bottom and top.
  - Holder parked 46 mm and 52 mm in for protons respectively at LHC flat bottom and top.

- Conclusions.
Comparison between measurements and simulations: gonio parked out with crystal (1/2)

2017 measurement
2019 measurement
Simulation (15 CMW)

Green square: OK (when shift in $f_r \leq 5\%$, $R_s$ and $Q$ not considered)
Red square: not OK
M: missing mode
Comparison between measurements and simulations: gonio parked out with crystal (2/2)

**2017 measurement**

**2019 measurement**

**Simulation (15 CMW)**

Green square: OK (when shift in $f_r \leq 5\%$, $R_s$ and $Q$ not considered)

Red square: not OK

M: missing mode

**TOTAL MATCHES**

S vs 2017

4/9

S vs 2019

5/9
Comparison between measurements and simulations:

gonio parked 40 mm in with crystal (1/2)

Green square: OK (when shift in \( f_r \leq 5\% \), \( R_s \) and \( Q \) not considered)
Red square: not OK
M: missing mode
Comparison between measurements and simulations: gonio parked 40 mm in with crystal (2/2)

- **2017 measurement**
- **2019 measurement**
- **Simulation (15 CMW)**

**Graph:**
- Green square: OK (when shift in $f_r \leq 5\%$, $R_s$ and $Q$ not considered)
- Red square: not OK
- M: missing mode

**Total matches:**
- $S$ vs 2017: 5/10
- $S$ vs 2019: 5/10
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Holder parked out with crystal for protons: beam Fill5979

- Beam used in 2017, 2556 bunches, 1.1e11 ppb, Gaussian distribution, flat top.
- 25 ns bucket length, $T_{\text{rev}}=86\ \mu\text{s}$.

Filling scheme

- Zoom 1 (batches)
- Zoom 2 (bunches)
- Zoom 3 (bunch)

Power spectrum $|\sigma|^2$

Re $Z$ (simulation in slide 41)

Holder parked out with crystal

Power loss = 

$$ (f_{\text{rev}} e N_b)^2 \sum_{p=-\infty}^{+\infty} |\sigma(p f_{\text{rev}})|^2 \text{Re } Z(p f_{\text{rev}}) $$

beam intensity

= 6.70 W
Holder parked out with crystal for protons: HL beams

- **Beam HL2760b**: 2760 bunches, $2.3 \times 10^{11}$ ppb, 25 ns bucket length, Gaussian distribution with rms 1.2 ns.

  - **Filling scheme**
  - **Power spectrum**
    \[ |\sigma|^2 \]
    - **Power loss** = 18.03 W

- **Beam 8b4eHL**: 8 bunches and 4 empty buckets for electron cloud mitigation, 1972 bunches, $2.3 \times 10^{11}$ ppb, 25 ns bucket length, Gaussian distribution.

  - **Filling scheme**
  - **Zoom 1 (batches)**
  - **Power spectrum**
    \[ |\sigma|^2 \]
    - **Power loss** = 14.16 W
Crystal parked 46 mm in (LHC flat bottom) or 52 mm in (LHC flat bottom): impedances

Update in Oct. 2019

- The distance between beam and crystal is set (on average) to 8 mm and 2 mm at LHC flat bottom and top respectively (slide 8).
- Wakefield simulations with the same model and assumptions used for the simulations with crystal parked out (slide 41) or 40 mm in (slide 43):
  - complete goniometer model
  - CMW=15, characterization of materials, ...
- $R_s$ of the mode at 710 MHz increases as $70 \, \Omega \rightarrow 6000 \, \Omega \rightarrow 9800 \, \Omega \rightarrow 18400 \, \Omega$ when holder and crystals are 0 mm in -> 40 mm in -> 46 mm in -> 52 mm in.
  - Slides 37 and 39 showed that this mode is mostly due to the holder.
Crystal parked 46 mm in (LHC flat bottom) or 52 mm in (LHC flat bottom) for ions: power losses

Update in Oct. 2019

- The considered beam was used in the last part of the 2018 run (fill 7467 and later).
- Batches of three bunches separated by 75 ns (three buckets), 730 bunches in total.
- Gaussian bunch distribution with rms 0.275 ns (at the start of the fill).
- Pb ions per bunch: 2.1e8.

Power losses at LHC flat bottom and top: 1.13 W and 0.25 W respectively.
This order of magnitude was expected comparing this beam with the HL2760b proton beam (slide 47):

- Expected power for constant impedance: $18 \text{ W} \times 82 / (1000 \times 4) = 0.37 \text{ W}$

Data for HL ion beams are not available yet. However, as a worst case, the power loss will be 5 W.
Crystal parked 46 mm in (LHC flat bottom) or 52 mm in (LHC flat bottom) for protons: power losses

Even if this scenario is not probable, power losses were also computed for the case of protons with the crystal parked 46 mm in (LHC flat bottom) or 52 mm in (LHC flat top).

- **Power losses at flat-bottom:**
  - Beam Fill5979 -> 105.24 W
  - Beam HL2760b -> 384.29 W
  - Beam 8b4eHL -> 241.70 W

- **Power losses at flat-top:**
  - Beam Fill5979 -> 29.32 W
  - Beam HL2760b -> 80.72 W
  - Beam 8b4eHL -> 90.20 W

Although the mode shunt impedances are generally higher at LHC flat top than bottom, the values of power losses are significantly larger in the second case.

- In fact at flat bottom the mode resonant frequencies are on average closer to the spectrum larger-amplitude components.
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- Conclusions.
The characterization of the longitudinal impedance of the LHC goniometer has never been satisfactorily performed since 2014.

A LHC gonio (version V2, already measured in 2017) was available in 2019 for new RF measurements.
- The corresponding CAD was also available in 2019 to perform related electromagnetic simulations.

In this talk an overview of the features of the goniometer V2 was given:
- dimensions, adopted model, material characterization and interesting positions for the crystal.

A new analysis of the 2017 wire and probe measurements was performed:
- Two anomalies were found in the wire measurements results.
- Agreement of 52% between probe and wire measurements.

The 2019 wire and probe measurements were carefully analysed for the first time.
- The procedure used to obtain the impedance from the scattering parameters was explained in details.
- Agreement of 63% between probe and wire measurements.

2017 measurements were compared with 2019 measurements.
- The agreement was only partial and some important discrepancies were found.

Wakefield simulations for the cases of goniometer parked out or 40 mm in have been performed in order to compare the results with RF measurements.
- A not-simplified model was used, some numerical consistency checks were performed and the characterization of the different resonant modes was carried out.

Comparisons of 2017/2019 RF measurements with simulations show only a partial agreement:
- the agreement is roughly 50%, neglecting discrepancies in shunt impedance and quality factor.

Impedance simulations for realistic LHC scenarios allowed power-loss estimations
- Protons: values varying from 6.7 W to 384.3 W, depending on the beam and crystal position.
- Ions: the most recent beam was studied, with a power loss of 1.13 W and 0.25 W respectively at flat bottom and top. Data on HL beams unavailable, but a worst-case estimation of power is 5 W.