UA9 goniometer longitudinal impedance studies

Analysis of previous results, first advancements and plans for 2019

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Acknowledgements for material and information:

N. Biancacci, G. Castorina, A. Danisi, H. Day,
I. Lamas Garcia, A. Mostacci, A. Passarelli, B. Salvant,
M. Scisciò
Motivations (1/2)

- The goniometer is a device for beam-collimation.
  - It uses a silicon crystal to bent halo particles.
  - It has been proposed to be operationally used in the HL-LHC scenario.

- It is important to estimate the impact of the goniometer impedance on the overall LHC impedance budget.
  - Transverse and longitudinal impedance studies have been performed since 2012.
  - Only longitudinal impedance studies are mentioned in this talk.
    - Importance of comparing EM simulations with RF measurements.

- First CST simulations in April 2012 by H. Day [7] comparing two scenarios:
Significant discrepancies obtained and absence of measurements.
Therefore in 2014 the studies started again.
- Since then and until today, many different persons have contributed.
- Unfortunately, the goniometer impedance is largely not characterized yet.

Due to the large frame of time (2014-2018) and the numerous results coming from different persons using diverse assumptions, it is not straightforward to take stock of the situation.

Therefore in this talk the main results coming from the period 2014-2018 are analyzed.
- The main assumptions behind some of the most significant performed simulations are clearly underlined (thanks to M. Scisciò).

First advancements in simulations and plans for 2019 are finally mentioned.
Tools and strategies used in measurements

- The goniometer (DUT) is connected to a Vector Network Analyzer.
- Two different types of measurements give the S-parameters [1]:
  
  **Wire measurements**

  ![Wire measurements diagram](image)

  Attenuator (to reduce reflections)

<table>
<thead>
<tr>
<th>Port 1</th>
<th>VNA</th>
<th>Port 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>247 Ω</td>
<td>10 dB</td>
<td>247 Ω</td>
</tr>
<tr>
<td>0.5-mm wire</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

  Matching resistor (50 Ω <-> 300 Ω)

  - For wire measurements, the transmission across the DUT ($S_{21}^{DUT}$) is measured and compared to an ideal reference ($S_{21}^{REF}$).
    - Their ratio $S_{21}^{DUT} / S_{21}^{REF}$ is then converted to beam-coupling impedance [2]:

    **Log formula**
    \[
    Z_{\text{log}} = -2Z_c \ln \left( \frac{S_{21}^{DUT}}{S_{21}^{REF}} \right)
    \]
    
    $Z_c$: line impedance of DUT plus wire
    $Z_c (\approx 300 \, \Omega) = Z_{VNA} (=50 \, \Omega) + Z_{MR} (\approx 250 \, \Omega)$

  - Probe measurements can be used to obtain the resonant frequencies and quality factors of the goniometer resonant modes.

  ![Probe measurements diagram](image)
Tools and strategies used in simulations

- CATIA files of different versions of the gonio have been provided along the years:
  - CAD V1, Strip (ST) crystal
  - CAD V2, Quasi-mosaic (QM) crystal
  - CAD V3 (prototype), QM crystal

- Four different types of electromagnetic simulations have been performed with CST:
  - Wakefield simulations give directly the impedance table.
  - Eigenmode simulations provide the eigenmodes.
    - Often used as a benchmark against wakefield simulations (sum of eigenmodes = impedance table).
  - Time and frequency domain simulations give the S-parameters.
    - The wire-measurement setup (wire, matching resistor, 50 Ω coaxial) are modelled and included in simulations.
    - Often used as a benchmark against wakefield and eigenmode simulations (peaks of S-parameters and eigenmodes occur at the same resonant frequencies).
Contents

- Motivations.
- Tools and strategies used in measurements and simulations.
  - Description of CAD V1.
  - Parking position (CAD V1, 2014/2015, D. Alesini et al.).
    - Measurements and simulations.
  - Operational position (CAD V1, from 2014 to 2018, A. Passarelli et al.).
    - Measurements and simulations.
  - Summary.
  - Description of CAD V3.
  - Operational position (CAD V3, 2018, M. Scisciò et al.).
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  - Summary.
- Part 3. First advancements and plans for 2019 (2019, D. Quartullo et al.).
  - CAD V3, discrepancy between eigenmode and wakefield simulations in Part 2.
  - Goniometer V2, review of 2016/2017 measurements and preliminary wakefield simulations.
  - Conclusions and next steps.
This CAD represents the operational position for the gonio (shielding cylinder parked out):

- Crystal and holder are in the center of the gonio and aligned with the beam:
  - The beam line crosses the thin crystal (slide 8).
- Unrealistic, their distance should be a few rms of the transverse distribution.

- CAD received in 2014 and used till 2018 for CST simulations.
No information about the materials of the components in the CAD:

- All have $\varepsilon_r=1$, $\mu_r=1$, $\sigma_{el}=0$ S/m (i.e. vacuum).

Some names are in Italian.

- From 2014 to 2018, the crystal material has been always set to the CST library-material ‘silicon (lossy)’:
  - $\varepsilon_r = 11.9$ for all frequencies, $\sigma_{el}=2.5\times10^{-4}$ S/m, etc.

- From 2014 to 2018, the materials of the other components have been set either all to PEC (unrealistic, wakes don’t decay) or all to stainless steel 316LN ($\sigma_{el}=1.3\times10^6$ S/m at 20°C, more realistic).
  - Stainless steel is largely present (e.g. tank), but there are also aluminum, titanium, ceramic etc.

The crystal is in silicon: characterization at high frequencies (2-4 GHz) of its $\varepsilon'$ and $\tan\delta$ was done in 2016 [8].
CAD V1_mod (g7ab0100_C step file)

- CAD V1_mod is a modification (and simplification) of CAD V1.
- Operational position (shielding cylinder parked out).
- Two positions for crystal and holder:
  - Center of goniometer (exactly as before).
  - Very far from the center (parked out).
    - Unrealistic, since the rail should follow the holder.
- ST crystal.
- No information on the materials.
Differences between CAD V1 and V1_mod

- Significant differences between CAD V1 and V1_mod, both inside and outside the tank.

- Since 2014, CAD V1_mod has been rarely used in simulations.
Parking position: 2014 [1]

- Parking position of the goniometer studied by A. Danisi in 2014 using the CAD V1.
  - Shielding cylinder aligned with the beam pipe.
  - Holder and crystal parked out.

- The shielding cylinder closes the beam pipe to isolate it from the goniometer and therefore reduces the overall impedance.
- Toroidal RF contacts guarantee electrical continuity.
  - However airgaps are formed which cause a perturbation to the beam-pipe wall continuum.
- Measurements and simulations were needed to assess the impact of these airgaps on the impedance.

- Wire and probe measurements showed resonance peaks all located above 2.2 GHz, far from the nominal beam spectrum.
  - Good agreement in resonant frequencies.
  - Multiple scans (i.e. wire positions in the horizontal plane and probe positions) showed no significant variations of the resonant frequencies.
- Wire measurements results were compared with CST time-domain simulations (slide 13).
  - Incidentally, discrepancies were seen between wire and probe measurements when the shielding cylinder was parked out (operational position):
    - Peaks appeared only with wire measurements.
    - Probably measurements with crystal and holder, with the rail parked out.
    - Related simulations performed by A. Passarelli (slide 14).

- The two airgaps were modelled in CST as "parasitic pill-boxes".
- First approach: wakefield simulations with stainless steel as background.

Models in CST

Vacuum of the final object to be simulated.

Simulations results

Very small amplitude, it would lead to a measured normalised $S_{21}$ of ~ -0.003 dB.
-> Small value confused with measurement uncertainties.
-> Difficult to measure.

Second approach: time domain simulations modelling also the wire-measurement setup.

Background: PEC

0.5 mm wire

50 Ω coaxial waveguide port

Matching resistor 247 Ω

Measurements agreed with simulations, peaks above 2.2 GHz came from measurement setup.

Gonio in parking position didn’t show significant contributions to longitudinal impedance.
Operational position: 2014

- The CAD V1 has been simplified several times in 2014 by A. Passarelli who performed [4]:
  - CST wakefield simulations using very simplified models.
  - Assumptions: PEC for all materials, except for crystal in silicon.
  - Crystal and holder float in the vacuum (unrealistic).

- CST time-domain simulations using a simplified model (V1_simp) which includes most of the internal features of CAD V1.
  - PEC for all materials, except silicon for crystal.
  - Simulations with the rail parked in, without crystal and holder.
  - Comparison with wire measurements (with likely crystal, holder and rail parked out, slide 12).
  - The measurements setup (wire, resistors, etc.) was included in simulations.

V1_simp model

Results: $S_{21}$ vs frequency

Disagreements

- Wire and probe measurements were repeated in November 2015.
- A new version of the goniometer was used for these measurements.
  - CAD or photo is missing.
- Probe measurements were again not conclusive:
  - Difficulty to significantly excite and record modes above the noise level.
- Wire measurements showed more content.
- Wire measurement setup:
  - Matching resistors: 270 Ω per side.
  - Attenuators: 10 dB per side.
  - Wire: CuBe (copper beryllium), 0.5 mm diameter.
  - Frequency range: 50 MHz – 2 GHz.
  - Parameters: crystal position (from parked out to parked in) and shielding cylinder (from parked out to parked in).
A mode at about 490 MHz is introduced by the crystal and modulated by its position:
- Impedance increases when the crystal is approaching the beam line, it stays in the noise level when the crystal is in parking position.

A mode at about 850 MHz is independent from the crystal motion.
- The impedance is perturbed when the shielding cylinder is moved up and down:
  - This mode may be due to resonances (in the vacuum tank) close to the shielding cylinder.

Note: the rail and the holder move together with the crystal.

- A quite simplified model was used in simulations.
  - Simpler than what used in 2014 (V1_simp, slide 14).

- Several types of simulations were performed:
  - Eigenmode, wakefield and time domain (with and without the measurement setup).

- Simulations were with rail and holder in the center (probably without crystal).

- In eigenmode simulations, steel was used as material for all components.

- For the other types of simulations, probably steel (or another lossy metal with finite el. conductivity) was used as material for all components.
The different types of simulations agree concerning the resonant frequencies of modes 1 and 2.

- R and Q significantly larger in eigenmode simulations than in wakefield simulations.
- Modes 1 and 2 are not due to the measurement setup.
- Disagreements with measurements (slide 16).
In 2018, G. Castorina and M. Sciscio’ continued the simulations on the operational position of the gonio.

- Goal: make simulations agree with measurements.

They used the simplified model V1_simp (slide 14).

- Rail in the center of beam pipe, without crystal and holder.

Differences between CAD V1 (top) and V1-simp (bottom).

- The components outside the tank can be safely removed since they don’t affect the beam.
- But significant changes also inside (e.g. shapes and sizes of shielding cylinder and relative aperture).
Operational position: 2018, simulations results, without holder and crystal [6]

Wakefield simulations

- All materials are PEC
  - wake does not decay.
- Simulated wavelength: 50 m.
- 10 cells per wavelength (max freq.=1.5 GHz).

Eigenmode simulations

- Agreement in resonant frequencies with wakefield simulations (no analysis of R and Q).
- Modes 3 and 4 are due to the shielding cylinder, the others to the mechanical stage and the components on top of it.
- Note: modes 1 and 4 match with 2015/2016 measurements (slide 16).
Operational position: 2018, simulations without holder and crystal vs measurements [6]

- Simulations compared with ‘new’ (2016/2017) measurements done on even another goniometer with different internal structure and crystal type [2] (CAD V2, see Part 3).
  - Discrepancy between model used in simulations (derived from CAD V1) and goniometer used for measurements (CAD V2).

- Simulation: rail in the middle, without crystal and holder (slide 19).
- Measurement: rail and holder parked out, with crystal.
  - Not the same conditions in measurements and simulations.

- Agreement in resonant frequency for modes 4, 5 and 6.
- Inconsistency between measurements doing a scan of the wire vertical and horizontal positions.
  - Result from horizontal scan is wrong.

Measurements
Operational position: 2018, simulations improvement, without holder and crystal [6]

- Discrepancies between measurements and simulations led to additional wakefield simulations.
- **1st improvement** (G. Castorina): same simulation as previous slide, but with wavelength 200 m.
- **2nd and last improvement** (M. Scisciò): same simulation, but with 316N steel instead of PEC, wavelength 300 m, relatively dense mesh (steps: $dx=1.5$ mm, $dy=1.5$ mm, $dz=1.5$ mm, see slide 26).

The resonant frequencies don’t change improving the simulations assumptions.
- Conclusions of slides 20 and 21 don’t change.
Operational position: 2018, simulations, with holder and crystal [6]

- Wakefield simulations, using V1_simp and a very simplified model of the holder.
- 50 m wavelength, PEC for all materials except for crystal (silicon), 10 cells per wavelength.
- Holder is turned by 180° with respect to its real position.
- The rail is always in the center while holder and crystal move.

Model (holder moves horizontally)

Introducing crystal and holder in the center of beam pipe does not add new modes (slide 22).

Changing the holder and crystal position only modes 5 and 6 are affected.
Common improvements: the simplified holder is replaced with the one from CAD_V1, 36 cells per wavelength.

First improvement: 200 m wavelength, PEC for all materials except for crystal (silicon).

Second improvement: 200 m wavelength, 316N steel for all materials except for crystal (silicon).

Comparing with first improvement, R drops using steel, resonant frequencies don’t change.

Significant discrepancies with the simulation results in slide 23:

- Impedance spectra are very different for all frequencies when holder and crystal are introduced.

It seems that the introduction of crystal and holder lowers the resonant frequencies of the modes.

The peaks above 1 GHz disappear.
Measurements [2]: holder 40 mm in (~ in the center), without and with crystal

Without crystal (red vs orange):
- Holder in measurements but not in simulations.
- Modes 2 (480 MHz) and 3 (840 MHz) agree in resonant frequency.
- Discrepancies for other modes, e.g.
  - High-R peak at 660 MHz only in simulations.
  - Mode 1 only in measurement.

With crystal (black vs blue):
- Modes 1 (600 MHz) and 4 (1.1 GHz) agree in resonant frequency.
- Discrepancies for other modes, e.g.
  - Modes 2, 3 and 5 only in measurements.

Conclusion: significant discrepancies between measurements and simulations.

Note: discrepancies between 2015/2016 measurements (slide 16) and these measurements (black curve):
- Agreement only for mode 3.
- Different gonios and crystals (V1 vs V2) but same conditions.
Numerical discrepancies in CST due to mesh and modeling

- Wakefield simulations without crystal and holder (slide 22, ‘2nd improvement’), different meshes:
  - A: 10 cells_per_wavelength and other settings lead to min_mesh_step = 2 mm, max_mesh_step = 5 mm.
  - B: uniform mesh with dx=2, dy=2, dz=2 mm.
  - C: uniform mesh with dx=1.5, dy=1.5, dz=1.5 mm.
  - Improving the mesh from A to C, the frequency of mode 1 changes from 743 MHz to 762 MHz and back.
  - Similarly R of mode 2 increases and decreases.

- Wakefield simulations with crystal and holder (slide 24, ‘2nd improvement’), different treatments of the same model:
  - Two a priori equivalent ways:
    - A: Model in steel (vacuum as background).
    - B: Model in steel with its internal vacuum added to the simulation (PEC as background).
  - Discrepancy in R (~ factor 1.5) for mode 1.
Summary for Part 1

- Longitudinal impedance studies on the UA9 goniometer have been carried out from 2012 to 2018 by different persons.

- The parking position scenario (shielding cylinder parked in) was successfully treated in 2014.
  - Agreement between measurements and simulations.
  - It was showed that this scenario should not affect the beam.

- Issues were found for the operational position scenario (shielding cylinder parked out):
  - Different goniometers, CAD versions, types of measurements and assumptions for CST simulations along the years.
  - Sometimes measurements were compared with simulations using different assumptions.
  - Sometimes the model used in simulations didn’t correspond to the goniometer used for the measurements.

- Significant disagreements comparing measurements with simulations.
  - It has not been possible to successfully treat this scenario.
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  - Conclusions and next steps.
Due to the discrepancies between measurements and simulations, M. Sciscio’ asked in May 2018 an updated CAD model.

- He received a new CAD (version V3) and worked on that till the end of 2018.
- V3 CAD is related to a future goniometer not yet produced (prototype).
- Comparisons with measurements related to gonio V2 (see Part 3) were also performed.
  - Significant only if the changes in the V3 version with respect to the V2 version do not affect the impedance.
- Another type of crystal is used in CAD V3 (and V2): QM (Quasi-Mosaic), made of silicon.
- No information on the materials in CAD V3 (and V2).

Some differences between CAD V2 (left) and CAD V3 (right).

- Zoom of the QM crystal in CAD V3 (parked in, crossed by the beam).

Photo of QM crystal in goniometer V2.
Operational position: 2018, CAD V3, different configurations

- Four different configurations for CAD V3:
  - Rail parked in, without (left) and with (right) crystal-holder.
  - Rail parked out, without (left) and with (right) crystal-holder.
First approach: wakefield simulations starting from the CAD ‘rail parked in, without crystal-holder’.
- The external parts of the goniometer are removed, holes are covered by caps.
  - Removing these external parts implies changes inside the vacuum tank (maybe negligible effects).
- The obtained model is called V3_not_simp.

Operational position: 2018, CAD V3, preparation for wakefield simulations

- CAD V3
- V3_not_simp
Simulation results with V3_not_simp compared with other two wakefield simulations:

- One using CAD V1 without simplifications (V1_not_simp).
- The other using the model V1_simp.

Simulation results are also compared with measurements (V2 version, slide 21).

Assumptions for V3_not_simp simulation:

- 316LN steel for all goniometer elements;
- 20 cells per wavelength;
- Wavelength 300 m.

Each of the three simulations was performed by a different person.

- Probably similar assumptions were used (e.g. steel for materials, wavelength).

V1_simp curve practically corresponds to the one in slide 22 ('2nd improvement'), as it should.

Significant disagreements among the three simulations and measurements.

Note 1: if results from V1_not_simp are correct, then the model V1_simp is too simplified.

Note 2: if results from V1_not_simp are correct, then they are still quite different from measurements results using almost the same conditions (red curve in slide 25).
Second approach: eigenmode simulations to compare with wakefield ones starting from **V3_not_simp**.

- It was cumbersome to perform these simulations, since CST could apply meshes to a so detailed geometry only if a large number of hexahedrons was used (36.5e6 cells to have 6 cells per wavelength).
- The idea was to simplify **V3_not_simp** into another model **V3_simp**.
  - Wakefield and eigenmode simulations could then be compared.
  - The simplifications done inside the vacuum tank could be too strong (slide 34, and also 32).
Comparison of simulation results using V3_not_simp and V3_simp:

- V3_simp leads to a very different impedance table.
  - However, since eigenmode simulations were possible in this case, V3_simp was used to compare eigenmode and wakefield simulations.

Parameters for V3_not_simp:
- Steel for all elements.
- 20 cells per wavelength (~12e6 cells).
- 300 m wavelength.

Parameters for V3_simp:
- Steel for all elements.
- 60 cells per wavelength (~12e6 cells).
- 200 m wavelength.
The goal was to compare the modes from wakefield and eigenmode simulations:

- In wakefield simulations f, Q and R were obtained fitting the impedance table with resonator impedances.

- To check the correctness of the fit, the wake potential from the wakefield simulation (using a Gaussian bunch with rms=75 mm) was compared to the one reconstructed analytically using the modes of the fit (and the same Gaussian bunch).
  - The good agreement indicated that the fit was accurate.

Operational position: 2018, CAD V3, modes from wakefield simulation with V3_simp

Direct from CST
Reconstructed from fit

W(s) [V/pC] vs s [m]

Courtesy M. Sciscio’
Some assumptions for the eigenmode simulation:

- Steel for all the goniometer components.
- Tetrahedrons used with 30 cells per wavelength.

Result of the comparison (max frequency considered is 1.365 GHz):

<table>
<thead>
<tr>
<th>f [GHz]</th>
<th>Q</th>
<th>R [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
<td>133</td>
<td>71</td>
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<tr>
<td>0.517</td>
<td>388</td>
<td>1050</td>
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<td>0.538</td>
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<tr>
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<table>
<thead>
<tr>
<th>f [GHz]</th>
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Frequencies of the modes roughly agree in the comparison (see e.g. colored boxes).

However significant discrepancies in Q and R, without clear pattern.
Dicember 2018: CST time and frequency domain simulations of V3_simp including the typical goniometer wire-measurement setup (see e.g. slide 13):

- Wire in CuBe, diameter 0.5 mm.
- All the other materials are in 316LN steel.
Operational position: 2018, CAD V3, time/freq. domain simulations with V3_simp (2/2)

- Assumptions in frequency domain simulations:
  - Vacuum carved out from the model, steel as background (wire and lumped resistance are included).
  - Tetrahedrons used with 10 cells per wavelength (equilibrate mesh ratio of 1.5).
  - Frequency range: from 0.1 GHz to 1.5 GHz.
  - Boundary conditions: open (PML) along wire direction, otherwise electric ($E_{tang}=0$).

- Assumptions don’t change in time domain simulations, except for:
  - Hexahedrons are used with 60 cells per wavelength (but no equilibrate mesh ratio).
  - Since number of cells increases fast, two simplifications have been done:
    - Square cross-section for the wire.
    - Coaxial cable eliminated at both ends of the beam pipe.
Operational position: 2018, V3_simp, time/ freq. domain simulations results

- Time and frequency domain results were compared:
  - Good agreement in the resonant frequencies of the different modes.
  - Only slight differences in $S_{21}$ amplitudes.

- Frequency domain simulations were compared with measurements related to the V2 gonio, case ‘holder and crystal parked in’ [2]:
  - V2 and V3 gonio versions are different and simulations were without crystal and holder.
    - This comparison was only indicative.
  - Several discrepancies were found.
Summary for Part 2

- In 2018, several longitudinal impedance simulations were performed on a prototype version of the goniometer supposed to be installed in the future (version V3).

- Different types of CST simulations were compared using a simplified version of CAD V3:
  - Wakefield vs eigenmode simulations:
    - Reasonable agreement for the resonant frequencies.
    - No agreement for R and Q.
  - Time-domain vs frequency-domain simulations, including the wire-measurement setup:
    - Good agreement was found.

- Wakefield simulations showed that the simplified model V3_simp provides an impedance table very different from the one obtained with CAD V3 (and similarly for V1_simp and CAD V1).

- Simulation results were also compared with measurements related to the version-V2 gonio:
  - Version V3 is different from version V2, in addition different assumptions were done in simulations and measurements.
    - Comparisons were just indicative.
  - Several discrepancies were found.

- It was not possible to satisfactorily treat the operational position of the V3 gonio.
Contents

- Motivations.
- Tools and strategies used in measurements and simulations.

  - Description of CAD V1.
  - Parking position (CAD V1, 2014/2015, D. Alesini et al.).
    - Measurements and simulations.
  - Operational position (CAD V1, from 2014 to 2018, A. Passarelli et al.).
    - Measurements and simulations.
  - Summary.

  - Description of CAD V3.
  - Operational position (CAD V3, 2018, M. Scisciò et al.).
    - Simulations.
  - Summary.

Part 3. First advancements and plans for 2019 (2019, D. Quartullo et al.).
  - CAD V3, discrepancy between eigenmode and wakefield simulations in Part 2.
  - Goniometer V2, review of 2016/2017 measurements and preliminary wakefield simulations.
  - Conclusions and next steps.
CAD V3: discrepancies between eigenmode & wakefield simulations

- Further analysis to solve the discrepancies found in 2018 (slide 36).
- First step: impedance as sum of eigenmodes compared directly with the impedance table from the wakefield simulation.
  - Modes not circled:
    - Slight shift in frequency downwards and $R$ larger (~ factor 2 or more) for eigenmode impedance.
  - Modes circled in red are missing in eigenmode impedance.
  - Modes circled in yellow seem swapped.

- Second step: $R$ is recomputed in the eigenmode simulation post-processing specifying that $\beta=1$.
- Third step: $R$ is divided by 2 to compensate for the different definitions of $R$ in eigenmode and wakefield simulations [9].
  - No missing modes or swaps anymore.
  - Still some discrepancies in $R$ and slight shifts in resonant frequencies around 600 MHz.
Goniometer V2: intro

- For the first time in 2019 the CAD V2 (left) was received for CST simulations. Two scenarios:
  - Holder and crystal parked out (center).
  - Holder parked in, with beam line crossing the center of the crystal (right).
    - Unrealistic, the crystal should have a distance of a few rms from the crystal.

- The gonio V2 was installed during EYETS 2016/2017.
- The last and most reliable measurements were done in 2016/2017 on this gonio [2].
  - RF measurements on gonio V2 will be repeated at CERN in the end of June 2019 to confirm the last measurements.
- The first priority for 2019 is to match RF measurements and CST simulations of the goniometer V2 in operational position.
Wire and probe measurements on vertical gonio without crystal (left) and on horizontal gonio with crystal (right):

Wire measurements: LogFormula and ImprovedLogFormula used to derive Z from $S_{21}$:

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

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

R was generally larger using $Z_{\text{log}}$, but both formulas gave substantially the same Z.

$S_{21}^{\text{REF}}$: shielding cylinder parked in
Wire-measurements results (LogFormula):

- **ReZ: Holder parked out**
  - Above 800 MHz: modes at 840 MHz, 1.08 GHz and 1.15 GHz don’t significantly depend on the positions of the holder and the presence of the crystal.
  - Below 800 MHz, holder parked out: no modes without crystal, mode at 370 MHz with crystal.
  - Below 800 MHz, holder parked 40 mm in: two modes at 440 MHz and 480 MHz without crystal seem shifted in frequency upwards, to 605 MHz and 645 MHz, with crystal.
    - When the crystal is added, R increases by factor 1.5-2 and \( \Delta f_{3dB} \) increases as well.

- **ReZ: Holder parked 40mm in (~ in the center)**
  - 800 MHz
    - Above 800 MHz: modes at 840 MHz, 1.08 GHz and 1.15 GHz don’t significantly depend on the positions of the holder and the presence of the crystal.
    - Below 800 MHz, holder parked out: no modes without crystal, mode at 370 MHz with crystal.
    - Below 800 MHz, holder parked 40 mm in: two modes at 440 MHz and 480 MHz without crystal seem shifted in frequency upwards, to 605 MHz and 645 MHz, with crystal.
      - When the crystal is added, R increases by factor 1.5-2 and \( \Delta f_{3dB} \) increases as well.

- Probe-measurements results, only the $f_r$ were compared with wire-measurements (slide 45), not the Q:
  - Important mode at 370 MHz is missing (holder parked out with crystal).
  - Modes at around 1.08 GHz are missing.

<table>
<thead>
<tr>
<th>$f_r$ [MHz]</th>
<th>Q (holder parked out)</th>
<th>Q (holder 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>NO PEAK</td>
<td></td>
</tr>
<tr>
<td>447.93</td>
<td>NO PEAK</td>
<td>74.78</td>
</tr>
<tr>
<td>458.59</td>
<td>74.40</td>
<td>36.8</td>
</tr>
<tr>
<td>480.70</td>
<td>94.54</td>
<td>105.0</td>
</tr>
<tr>
<td>551.09</td>
<td>NO PEAK</td>
<td>26.68</td>
</tr>
<tr>
<td>638.02/614.80</td>
<td>105.14</td>
<td></td>
</tr>
<tr>
<td>753.45</td>
<td>NO PEAK</td>
<td>31.5</td>
</tr>
<tr>
<td>836.87</td>
<td>183.87</td>
<td>201.57</td>
</tr>
<tr>
<td>898.36</td>
<td>77.54</td>
<td>121.56</td>
</tr>
<tr>
<td>1164.36/1170.01/1153.70</td>
<td>194.24</td>
<td>295.71</td>
</tr>
<tr>
<td>1377.66</td>
<td>NO PEAK</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>NO PEAK</td>
<td>44.39</td>
</tr>
<tr>
<td>1473.02</td>
<td>86.82</td>
<td>81.72</td>
</tr>
<tr>
<td>1492.47</td>
<td>282.34</td>
<td>149.30</td>
</tr>
</tbody>
</table>
CAD V2 in 2019: safe simplifications and characterization of materials

- The original CAD was simplified only strictly outside the tank, paying attention not to modify anything that the beam could see.

- Effort was spent to better characterize the materials inside the vacuum tank.
  - Stainless steel ($\sigma_{el}=1.3e6$ S/m) predominates, but there are also:
    - Support for mirror and holder in aluminum ($\sigma_{el}=3.56e7$ S/m).
    - Piezo in ceramic ($\varepsilon_r=30$, $\sigma_{el}=1e-7$ S/m).
    - Contact in gold ($\sigma_{el}=4.6e7$ S/m), mostly visible when holder is parked in.
    - Holder in titanium alloy Ti6Al4V grade 5 ($\sigma_{el}=5.85e6$ S/m), crystal in silicon (slide 8).
    - Mirror in glass ($\varepsilon_r=6.7$, $\sigma_{el}=1e-12$ S/m), likely barely visible.

This piston goes inside, it cannot a priori be removed.
CAD V2 in 2019: preliminary wakefield simulations with original model

Due to recent changes of plans/configurations, it is more urgent to assess possible limitations with high intensities proton beams when the holder and crystal are parked out. Therefore it was given priority to this scenario in simulations.

Assumptions: model not simplified with materials characterized (slide 47), 500 m wavelength, 10 cells per wavelength with smoothing mesh ratio 1.5 (smallest cell 1.3 mm, largest cell 19.6 mm).

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Modes frequency and amplitude:

Mode 1: significant shift in frequency (110 MHz), R substantially agrees.
Mode 2: slight shift in frequency (20 MHz), R significantly larger in simulation.
Modes 3 and 4: agreement in resonant frequency, R is larger in simulation
Further investigations are needed.
Conclusions and next steps

- Maybe for the first time possibility to clearly compare CST simulations with RF measurements using the same goniometer (version 2).
  - Wire and probe measurements on gonio V2 were already done in 2016/2017.
    - Reasonable agreements between them, except for few cases.
  - Measurements will be repeated in in the end of June 2019 to confirm the previous results.

- Discrepancies between eigenmode and wakefield simulations found in 2018 for the goniometer V3 have in part been solved.

- The most important materials inside the goniometer version 2 have been characterized.
  - The crystal in silicon still requires a dedicated study.

- Preliminary wakefield simulations of the CAD V2 without simplifications have been performed and compared with 2016/2017 measurements:
  - Case studied: operational position with holder and crystal parked out.
    - More urgent to understand since it involves high intensity proton beams.
  - Agreement in number of most important modes in measurements and simulations.
  - Clear correspondence two by two comparing modes in measurements and simulations.
    - Maybe possibility to treat each of the four pairs independently.
  - Most significant discrepancies: 110 MHz shift in frequency upwards for mode 1 in simulation, R larger by a factor of 3 for mode 2 in simulation.

- Next steps: - Preparation for the measurements to be done in June 2019;
  - Analysis of the correctness of the preliminary simulation results.
References


[2] A. Passarelli, N. Biancacci and D. Amorim, ‘UA9 Goniometer Measurements in Operational Position’, CERN Impedance Meeting 02/12/2016 (successive measurements on goniometer V2 with crystal and crystal characterizations were never presented).


