Special
Joint WP2/WP4 Meeting
Tue 26 May 2020, 9:30 – 11:30

Chairs:	Gianluigi Arduini, Rama Calaga
Speakers:	Nicolas Mounet, Ivan Karpov, Luis Eduardo Medina Medrano, Benoît Salvant
Participants (vidyo):	Simon Albright, Theodoros Argyropoulos, Xavier Buffat, Andy Butterworth, Elena Chapochnikova, Heiko Damerau, Riccardo De Maria, Ilias Efthymiopoulos, Aaron Farricker, Hector Garcia Morales, Frank Gerigk, Giovanni Iadarola, Sofia Kostoglou, Elias Métral, Yannis Papaphilippou, Giulia Papotti, Galina Skripka, Guido Sterbini, Rogelio Tomás, Giovanna Vandoni, Frederik Van Der Veken, Christine Vollinger, Carlo Zannini

AGENDA

MEETING ACTIONS

Nicolas	Provide a longitudinal impedance model for Run 2.
Nicolas, Benoît	Update the longitudinal impedance model of HL-LHC with VELO and updated crab cavity modes.

GENERAL INFORMATION (GIANLUIGI ARDUINI, RAMA CALAGA)

This is a special meeting, joint between WP2 and WP4, mainly devoted to longitudinal aspects in HL-LHC.

The minutes of the previous WP2 meeting were circulated, and **Galina** reviewed the comments received since then, which concerned the presentation made by **Sofia**:

- A discussion with **Hector** on the transverse distribution is ongoing. It was suggested to use a double Gaussian with $\sigma_2=2\sigma_1$ and $I_1/I_2=65/35$ but it remains to be determined if it's better to use a q-Gaussian or a double Gaussian. **Yannis** also mentioned the halo, and that an update of **Hector** studies would be worth presenting in a future meeting.
- Regarding the impact of the ADT on the high-frequency cluster but not on the low-frequency one, **Sofia** commented that this has to do with the fact that the high-f cluster has a large amplitude and it is "seen" and mitigated by the ADT, while the low-f cluster is lower than the ADT noise floor, which is <0.9 µm (number from **Martin Soderen** paper, Evian 2019) → We are able to observe these lines which are below the ADT noise floor because we combine multiple bunch information in the post-processing, while the ADT is looking at the single bunch signal. To verify this hypothesis, a measurement is foreseen, checking the amplitude of the high-f cluster when the ADT gain is further reduced or even switched off for a few minutes.
- **Gianluigi** asked what is the impact on lifetime of higher telescopic factors at constant beta*. This is important for HL-LHC. Is the noise on the main power converter going to be a limitation? **Sofia** replied that this can be checked. The main assumption is that the LHC noise spectrum will remain the same for HL-LHC (although this is not what we expect). Then the impact of changing the tele-index can be checked.

Gianluigi then reviewed the presentations of the previous WP2 meeting and the related actions:

- From the talk of **Sofia**, there is an action on the comparison of emittance growth due to noise and analytical models, and another one on the impact of the phase between dipole power converters. **Yannis** made a clarification regarding the last slide of the talk: if one distributes the noise around dipoles, the lifetime does not show any difference. Also, the simulations do not contain a unique kick, instead there is a change of position in the ADT (at the observation point), and there is a phase there. On the other hand, the impact of a change of phase between B1 and B2 has not been checked. **Gianluigi** asked what would happened if one changes the phase between harmonics and between sectors. **Yannis** said there is a phase, but it is averaged. After a millions of turns, **Yannis** does not think the phase will matter for the lifetime. Finally, **Gianluigi** highlighted the action about the test in a dipole, to check the suppression of noise in the beam screen.
- The talk of **Ezio** was an update about the field quality in the MCBRD corrector. This is not yet the final word, an update will come in June after new measurements. **Gianluigi** highlighted the importance to get measurements of the field quality, and to be in a situation similar to operation.
- Finally, **Frederik** had presented the impact of feed-down from b3 on dynamic aperture (DA). The end result is that DA is mostly driven by the multipoles themselves.

Regarding the previous WP4 meeting, **Rama** mentioned that RFD cavities for the SPS tests were built at CERN in Q1-2020. There was a delay due to Covid-19 for the processing and testing of the cavities. The goal was to test them before September and then send them to the UK in October. This will now happen in Q1-2021. The master schedule will be modified by Sept. 2020; in the end, the completion of the cryomodule is expected at the end of 2021. There was also an action which concerns WP2, regarding the confirmation of the optics in IR4 for the ADT; **Riccardo** and Wolfgang Hofle will look at them as soon as possible and it will come back to the TCC.

Concerning the meeting today, according to **Rama** the goal is to see what has to be done to get an improved longitudinal impedance model before the end of the year including the main changes for HL-LHC.

1 PRESENT STATUS OF THE LONGITUDINAL IMPEDANCE FOR HL-LHC (NICOLAS MOUNET)

The current LHC (Run 3) and HL-LHC longitudinal impedance models were presented. These were obtained as "by-products" of the transverse models, and hence have to be taken with a particular caution as the emphasis was put on equipment creating a large transverse impedance, which are not necessarily the most critical equipment regarding the longitudinal impedance. The content of the impedance models (which are available on the impedance web page, for their top energy version) were described and the most important contributions identified as being the broad-band ones (from pumping holes in beam screens, arc BPMs, bellows, vacuum valves, and RF & experimental cavities). The resistive-wall impedance from the beam screens also plays a significant role, as well as high order modes from cavities.

The models at injection and top energy are relatively similar, exhibiting a difference around 25-30% at 1 GHz. The LHC & HL-LHC models are almost identical on a broad frequency range if taken at the same energy, except for the high order modes from crab cavities in HL-LHC. The impact of the cutoff frequency chosen for the broad-band resonator model was also discussed: the most physical value (corresponding to the cutoff frequency of the beam screen) is 5 GHz but the models are currently using a larger cutoff of 50 GHz as in the transverse plane (which was chosen to be conservative, stability-wise, at high chromaticity); still 5 GHz seems a better value for the longitudinal plane, and the impact on the real part of the impedance in the GHz range is quite significant. More generally, there is room for improvement of the model of several broad-band contributors (in particular arc BPMs, bellows, vacuum valves, Y-chambers, and BI instruments) which are accounting for more than 20% of the current longitudinal impedance and are currently coming solely from evaluations done for the LHC design report.

- **Elias** commented that in the design report only a single value was provided for the imaginary part of Z/n, which might be fine (to be checked). The simplification which was then made is to include this within a broad-band resonator model, with a quality factor of 1 and a resonance frequency equal to the cut-off frequency of the beam screen of ~ 5 GHz. This can only be considered as a first model (which should already give quite some good results for some mechanisms), which needs then to be improved to have reliable results for all the phenomena linked to this

impedance. **Nicolas** agreed. This needs to be revisited as we develop a more accurate impedance model.

- **Gianluigi** wondered why the total seems to get higher than 100% on some part of the plots showing the various contributions to the models (slides 10 & 11). **Nicolas** answered that the contribution from resonant, narrow-band peaks can be negative for a shallow band of frequencies, hence the impedance of a few contributors can get above the total impedance. This is a standard problem on this kind of plot, that work perfectly well only if all contributions are strictly positive (which is the case at low frequency).
- **Elena** was surprised to see that the LHC & HL-LHC models were so close. She mentioned the results from the PhD thesis of **Juan Esteban Müller** which were showing instead a 20% difference between the two models in terms of Im(Z/n). **Elena** also insisted on the need to have a good model for Run 2, in order to benchmark with measurements, and compare it with the one after LS2. **Nicolas** said he will send the Run 2 model in its current state (Action: **Nicolas**).
- **Elias** commented that a precise longitudinal model was never really developed in the section (for none of the CERN machines), contrary to the transverse plane (also for Run 2). Indeed, our approach has always been to develop in detail the transverse impedance models and only apply to the longitudinal plane some of our studies, e.g. when we developed new formulae for the resistive-wall impedance, but all the other aspects need to be studied in detail to develop a precise longitudinal impedance model.
- **Rama** wondered if any large impedance contributor is already known to be missing from the model. **Nicolas** did not think so, but **Benoît** said the upgraded VELO could be one, as well as the fundamental mode from the crab cavities. **Nicolas** said the latter should be there; after the meeting he double checked and noticed that the fundamental mode in longitudinal is actually missing from the RFD cavities close to IP1. **Rama** asked if the VELO is currently being checked, **Benoît** answered in the positive (Action: **Nicolas, Benoît** - update the model for HL-LHC for the VELO and crab cavities).
- **Gianluigi** asked if there is still a reason to use a cutoff at 50 GHz for the broad-band model. **Nicolas** answered in the negative, especially in longitudinal; 5 GHz is more realistic.
- **Gianluigi** concluded that all the people involved should sit together and try to check and improve the model. **Rama** agreed and said a good model is needed within the next 6 months. **Elias** commented that the RF experts should indeed check equipment by equipment. **Elena** argued that it is difficult for them as the team is getting smaller. **Benoît** then said that they need some input from RF experts (e.g. **Elena** and **Ivan**) to understand which frequencies matter most. **Elena** agreed.

2 UPDATE ON LONGITUDINAL IMPEDANCE STUDIES FOR HL-LHC (IVAN KARPOV)

The loss of Landau damping in the longitudinal plane was studied using macroparticle simulations (thanks to the BLonD code) and a Van Kampen mode analysis (with the MELODY code), in an attempt to explain the discrepancy between Sacherer approach and Run 2 stability threshold measurements, as well as the

strong dependency of the threshold on the cutoff frequency chosen for the broad-band longitudinal impedance model (see previous talk).

The study used a resonator, broad-band impedance model (Q=1 and Im(Z/n)=0.07 Ohm) at two different resonance frequencies (4 and 8 GHz) with (HL-)LHC typical parameters at injection, and showed that a Van Kampen mode appears at around half the resonance frequency, explaining why the stability threshold strongly depends on the resonance frequency chosen even much above the bunch spectrum. The corresponding mode affects most strongly the center of the bunch, and hence might not be too dangerous. On the other hand, the modes widen at higher intensity and far above the threshold, do not depend much on the resonance frequency chosen.

The presence of these modes was verified in macroparticle simulations, as well as the behavior far above the threshold. On the other hand, such simulations were not conclusive regarding the behavior close to the threshold. Finally, it was shown that a kick (or injection error) can excite these modes; they can also be driven by noise, with potential impact on the controlled emittance blow-up.

- **Elias** asked if the loss of Landau damping is from a dipole mode, and if not what is the most critical mode. **Ivan** answered that it is a dipole mode.
- **Elias** asked if intrabunch oscillations were looked at when a loss of Landau damping was observed in the LHC, and wondered if the mode was in the center of the bunch. **Ivan** said that only the bunch position was recorded. **Elena** commented that it was not common to look at this kind of behaviour in the past; these are very recent findings. They looked at the Schottky spectrum and observed coherent modes there, but they did not have the insight about what to look for exactly.
- **Elias** then concluded that the cutoff frequency has really an impact. **Ivan** agreed and added that a high quality factor resonator with a high resonance frequency will not matter, but a broad-band imaginary impedance which is growing up to about a cutoff frequency defines the threshold.
- **Rama** asked how does the noise compare with the one during Run 2, and if we can explain what was seen on bunch length and bunch oscillations. **Elena** commented that there the bunches were not small when an intensity of 2e11 was injected. **Ivan** said that with shorter bunches the modes are indeed more separated, and parameters can be scanned to cover the right frequency region.

3 UPDATE ON HL-LHC INJECTION STUDIES (LUIS EDUARDO MEDINA MEDRANO)

The purpose of this talk was to investigate the capture losses at injection in the LHC & HL-LHC, and their sensitivity to energy errors, in the context of the higher RF power needed for HL-LHC and the reduction of the injection voltage for a better SPS-LHC matching. Direct beam and bunch-by-bunch (BBB) intensity measurements as a function of RF voltage in 2018, showed an increase of the average SPS-LHC transfer losses per injection from 0.1% at 6 MV to 0.2% at 4 MV. Fast BCT measurements taken every minute after injection, show the expected U-shape of the losses along the batches due to beam-loading compensation with feedback and feedforward in SPS at extraction. Dedicated measurements of bunch profiles on the

1st turn, on the other hand, were not accurate enough but provided the correct parameter space in terms of bunch length and tail population, for BLonD computations.

BLonD simulations using the 2018 longitudinal impedance model (with 50 GHz cutoff) and with a 4 MV injection voltage and 60 MeV energy error, were benchmarked against Run 2 BBB measurements (fill 7137), giving the correct magnitude for the losses but higher bunch lengths than obtained from the profile analysis.

First simulations for HL-LHC with both the 5 GHz and 50 GHz impedance models, with various bunch lengths and tail populations, showed that long bunches with long tails are above the 2% threshold of losses for large energy error (100 MeV). Still, the simulations are quite pessimistic as all bunches are assumed to have an identical profile. For better HL-LHC estimates in the future, one needs simulations with a bunch generation in the SPS and an improved cavity control model (OTFB).

- **Rama** mentioned that the idea to lower the voltage for the 2018 run actually comes from **Elena**.
- **Gianluigi** asked what the typical injection energy error is. **Luis** answered the maximum is around 60 MeV, but most of the time it is between 10 and 20 MeV. **Gianluigi** wondered then if the SPS is the main source of energy fluctuation. **Theodoros** answered that it was not clear what was the source of the cases with a large energy error. There are studies about SPS ripples, but it is not confirmed if it comes from them. **Elena** added there was an investigation from OP (by **Jorg Wenninger** and **Verena Kain**) which concluded that the fluctuations are from the SPS, but there are two kinds: fill-to-fill (which are small), and a slow drift. The mismatch is adjusted only in the LHC, and the SPS cannot do much. Tomography can help to do a better and automatic matching. In the design report 50 MeV were assumed; now the fill-to-fill variation is below 20 MeV from the SPS ripples, but this cannot be easily corrected.
- **Gianluigi** asked if with automatic tools, one can expect losses will be below 1% with 6 MV. **Theodoros** answered in the positive. He insisted that the plots of **Luis** on slide 17, are somewhat exaggerated since all bunches are the same. Losses are reduced thanks to energy matching, so probably will be below 1%. **Elena** confirmed but also mentioned that the SPS bunch distribution is not known, as there could be some halo with the Q20 optics. **Gianluigi** asked if, nevertheless, based on the simulations and knowing their caveats, 6 MV would be compatible with <1% losses and with the RF power (i.e. there is no need for an upgrade). **Rama** answered that 6 MV will likely be close to the RF power limit, without margin for feedback, etc. The RF power lines between all cavities are not all equal, and maybe not all of them can provide the required voltage, but 6 MV should be doable for steady state, with the exception of injection transients in the first turns. **Elena** also confirmed that 6 MV could be acceptable but with still some uncertainties. **Rama** finally said that a 20% margin is reasonable between the operating point and the maximum (300kW), but in some RF cavities the saturation is almost at 250 kW.
- **Gianluigi** then asked if 5 MV was tried. **Rama** said that for HL it is still very preliminary, and **Luis** has to run more simulations to see how the trend goes. **Gianluigi** mentioned that he understood from **Helga Timko** that the thresholds are quite conservative and one could go higher. **Rama** argued that with a systematic correction of 20-50 MeV or below, it has to be checked if 5 MV can be done. **Elena** added that ideal bunches (in terms of halo) should fit, but the issue lies in injection

errors; losses depend on the halo which is not well known, and one can start to lose because of noise. 6 MV was set at the time of Q26 in the SPS, but the longitudinal emittance is smaller with Q20 optics, which might allow to go to lower voltages.

- **Theodoros** was surprised that losses in slide 17 are significantly higher than measured. **Elena** also asked if the simulation parameters are different between the 5 & 50 GHz models, to which **Luis** answered he had to refine the slicing because of the 50 GHz model, but in the end chose the same parameters for both simulations (around 300 slices), to be able to compare.
- **Rogelio** wondered if the line in the plot of slide 17 (between 0 and 100 MeV injection energy error) is really a line. **Luis** answered that indeed it is not.

4 IMPEDANCE ESTIMATED OF RF FINGERS FOR CRAB CAVITY MODULE (BENOÎT SALVANT)

This presentation is a follow-up of the 170th WP2 meeting on the particular subject of the impedance of the deformable RF fingers as presented there. In their original design, deformable RF fingers (DRF) of the transitions in the crab-cavity cryomodule, were exhibiting indeed a much larger impedance than in other modules, due to their large convolution angle (~18 deg) and their length.

Here five designs are compared to the original one: the current unshielded bellow, two designs by **Cedric Garion** (with resp. 3 and 4 convolutions), and two new designs by **Teddy Capelli** (with resp. 2 and 3 convolutions, shallower). While the unshielded design is one order of magnitude higher in impedance than the original DRF, the four new designs are between 3 and 7 times better for both the longitudinal and transverse impedances, ending up into a much smaller impact on the overall impedance budget (contrary to the original design of the DRF). **Teddy**'s designs are the best impedance-wise, but are less standard than the ones of **Cedric,** which are used in other locations and hence already validated and tested. As a final note, the designs from **Teddy** can only be used in the crab cavities, where the extension to compensate is small and mainly transverse.

Benoît mentioned a comment from Christine before the meeting that we may need to account for the potential beam offset there, if it is large.

- **Riccardo** said indeed an offset is needed to accommodate the crossing angle. But **Gianluigi** said the cavity is aligned on the beam, so wondered why the beam could be far from the center of the bellow. **Riccardo** answered that each cryomodule is aligned on each beam (and the two cavities are aligned in the cryomodules), but with the crossing bump a shear appears between the cryomodules, as one beam goes in the opposite direction as the other, e.g. one cavity has to go up for B1, down for B2, so the bellow has to take this offset. **Gianluigi** asked if this is for all bellows or for only some of them. **Riccardo** answered it is for all of them. Crab cavities have to be aligned with inner tracking. D2 is aligned with the flat machine without crossing angle, then there are offsets. If the machine were perfect, the entire budget of the MCBRD could be allocated there and the offset could be zero, in principle; more realistically it can be as high as 300 microns. **Benoît** commented that 300 microns should not change the impedance. **Riccardo** said the vacuum

people are giving a maximum allowed offset, which also absorbs the manufacturing errors. **Rama** mentioned in addition the impact of going from 300K to 2K. The engineering proposal is based on a number of constraints.

- **Rama** mentioned that the final solution will be decided in a meeting on Thursday. In his opinion he sees no big difference between 2 or 3 convolutions, nor between **Cedric** and **Teddy**'s solutions, as the numbers are all small. **Elena** confirmed, and added that the uncertainty on the impedance is more than these additions to the impedance budget. **Benoît** agreed that the error in the simulations makes it hard to distinguish between versions of similar design, with different convolutions. **Benoît** said that the transverse impedance was checked, but that **Elena** should make a statement for the longitudinal plane as usual. **Elena** answered that one needs to make computations with the full longitudinal model. **Benoît** and **Gianluigi** said that one needs to decide on the solution adopted before these computations can be performed. **Rama** doubted one can conclude in a short time between one or the other; this is for the cryomodule built for the UK towards the SPS-tests, where there are already quite some delays. **Teddy**'s solution is on paper only, while **Cedric**'s one is already validated. For **Elena**, even 1% seems very small and acceptable (even if in general the politics is to try to find the best solution impedance-wise). **Benoît** confirmed, but the original DRF design was not as small as reasonably achievable, while the other two are optimized.

5 ROUND TABLE (RAMA CALAGA, GIANLUIGI ARDUINI)

In the coming months, the HL-LHC longitudinal impedance model will be looked at carefully.

The next WP2 meeting meeting will be on June 2nd, by video-conferencing, with the following agenda:

- HL-LHC IP and Ring BPMs: Read-out technology and expected BPM performance (Manfred Wendt),
- Review of the BPM specifications (Riccardo De Maria),
- Transverse stability margins from non-conformities and/or beam damage (Nicolas Mounet),
- Offsets at collimators and radiation considerations during the measurements of tune shifts in 2018 (Alessio Mereghetti).

The next WP4 meeting will take place in June.

Reported by N. Mounet