EXPECTED IMPACT OF HARDWARE CHANGES ON IMPEDANCE AND BEAM INDUCED HEATING DURING RUN 2

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Abstract

Following the significant impedance related issues that occurred during the LHC Run 1, all involved equipment groups made an impressive effort to assess and reduce the impedance of their near-beam components.

Concerning beam induced RF heating, many problems in Run 1 were linked to unexpected non-conformities. Mitigations were put in place but new non-conformities are likely to appear in Run 2, and this is why efficient monitoring and alarms are currently put in place. Besides, known limitations that led to increase the bunch length from 1 ns to 1.25 ns were removed, which would open the possibility to try and reduce the target bunch length at top energy. Regardless of the target bunch length, many components will need careful follow up in 2015 (e.g. TDI, BSRT, Roman pots, MKI, BGV).

Concerning the LHC impedance, announced hardware changes are expected to be transparent, but the new TCTP and TCSP collimators with BPMs and ferrites should be monitored closely, as well as the modified Roman pots, new TCL4 and especially new TCL6 collimators if they approach the beam with very low gaps at high beam intensity.

INTRODUCTION

During LS1, many hardware changes affected the CERN Large Hadron Collider (LHC) beam surroundings: consolidations, upgrades and new equipment. The expected consequences of these changes on the LHC beam coupling impedance will be reviewed in this contribution, as well as their consequences on the related intensity limitations: beam instabilities and beam induced RF heating. These collective effects have indeed affected the performance of the LHC before the Long Shutdown 1 (LS1), and this contribution will provide a status of the expected issues that may come up, as well as suggest mitigation strategies in case of problems.

CONTEXT

When an ultrarelativistic beam of particles traverses a device, which is not smooth (resp. is not a perfect conductor), it generates geometric (resp. resistive) wakefields that perturb the following particles. These electromagnetic perturbations are usually decomposed into longitudinal and transverse wakefields (or beam coupling impedance in frequency domain).

The longitudinal impedance leads to energy lost from the particle, dissipated at the surface or in the bulk of the neighbouring devices, which results in heating of the beam surroundings, temperature interlocks and/or degradation of machine devices. In fact, during Run 1, the LHC bunch length needed to be increased from 1 ns to 1.25 ns (4 sigma) to mitigate beam induced heating issues on several LHC components [1].

The longitudinal (resp. transverse) impedance also leads to perturbation of the synchrotron (resp. betatron) oscillations, which can excite longitudinal (resp. transverse) instabilities as well as degrade the beam quality (e.g. beam losses, emittance growth and dumps). Longitudinal instabilities could be generated during Run 1, but have never been a limitation, while many transverse instabilities occurred in LHC during Run 1, limiting the LHC performance in particular in the Summer of 2012 [2].

In case of a request for a modification, upgrade or installation of new components the current policy enforced by the impedance team is:

- The new/modified component should by default remain in the shadow of the current LHC impedance model in the relevant frequency range (8 kHz to about 2.5 GHz).
- New longitudinal resonant modes should present a shunt impedance below 200 kΩ (in circuit convention).
- The impact of new transverse resonant modes should be checked with beam dynamics computations or simulations.
- Expected heat loads are communicated to the equipment owner so that he can take appropriate action (e.g. cooling, improve thermal conduction and/or radiation to evacuate the heat load).

In case the beam induced RF heating is predicted to be too large, then there are several potential solutions:

- Reduce the longitudinal impedance at the LHC beam spectrum harmonics.
- Extract the heat and/or improve the resistance to heat of the critical parts of the device.
- Reduce the intensity per bunch, which is equally efficient with broadband and narrow band impedances.
- Reduce the number of bunches, which is less efficient with broadband impedances than with narrow band impedances.
- Optimize the beam power spectrum by changing bunch length but also bunch shape, e.g. with flat bunches [3].

It is clear that the equipment owner can only optimize the first two of these potential solutions. It is important to note that it is risky to design devices so that sharp high Q resonant modes are placed in between beam harmonic lines since both RF simulations and manufacturing/handling can lead to large uncertainties in the determination of the frequencies of these modes.

In case of unexpected issue, the beam parameters can be optimized, at the possible cost of adding new constraints to the operational parameter space if the solution has to be implemented on a permanent basis (as for the bunch length increase at flat top since mid-2011). For instance, in case a temporary heating problem is observed on a component during a fill, the bunch length and/or bunch shape could be optimized, instead of abruptly dumping the beam.

HARDWARE CHANGES DURING LS1

The changes before LS1 with potential impact on impedance were categorized into:

- *Consolidation changes that followed an issue observed before LS1:*

the consolidation of damaged injection protection collimators TDIs (reinforced beam screen, refurbished motor control and jaw holder) [4]; the replacement of the skew primary collimator TCP.B6L7.B1 with a spare due to temperature increase of the order of 50 degrees, which is larger by 1 to 2 orders of magnitude compared to all other LHC TCP collimators [5]; the replacement of the damaged mirror systems of the two synchrotron light monitors (BSRT) by new designs that are expected to generate less beam induced heating [6]; the replacement of non-conforming RF fingers [7]; the addition of shielding to the ATLAS-ALFA Roman pot in order to reduce beam induced heating [8].

- *Upgrade of existing components:*

the replacement of all tertiary collimators (TCTs) and the secondary collimator in IR6 (TCS) with the designs with embedded BPMs (TCTPs and TCSP) [9]: in particular, the two remaining two-beam vertical tertiary collimators (TCTVBs), for which the temperature was observed to increase significantly before LS1, were relocated outside the combined regions and replaced by these new TCT designs; the "TOTEM consolidation" of existing Roman pots by addition of new shielding [8]; the upgrade of the MKI beam screen design to include all 24 screen conductors instead of 15 or 19 before LS1 [10]; the new experimental beam pipe with smaller aperture in the central region of the ATLAS and CMS experiments [11]; the upgrade of the Schottky monitors [6]; the insertion of a NEG coated insert in the large diameter vacuum chambers [12].

- *Installation of new equipment:*

the collimators to protect from physics debris (TCL4 and TCL6 in IR1 and IR5) [9]; the installation of a third TCDQ module [10]; the installation of a new beam size monitor BGV on beam 2 [6]; the new "TOTEM upgrade" cylindrical Roman pots [8]; two goniometers for crystal collimation tests in IR7 [13].

Besides, some non-conformities were detected but it was decided to leave them in place: small RF contacts sticking inside the beam screens at three locations, including one triplet [7].

IMPACT OF HARDWARE CHANGES ON BEAM INDUCED RF HEATING

This chapter covers the changes that are expected to have the largest impact on beam induced RF heating after LS1: TDIs, BSRTs, Roman pots and MKIs (acknowledging the removal of the TCTVBs).

Injection Protection collimators TDIs

The TDI suffered from various problems before LS1: large outgassing with beam - which was a significant cause of background for the neighbouring experiments -, as well as several mechanical issues (deformation of the copper beam screen and beam induced deformation of the jaw), which have been a worry for the integrity of the device and machine protection. All these problems are believed to be linked to the large longitudinal impedance of the device and to the related beam induced heating that could not be mitigated by the water cooling that turned out to be inefficient [4]. Since there was no temperature monitoring installed before LS1, it has been difficult to understand what was going on only from vacuum pressure measurements. It has to be noted that the specification of the TDI as an internal dump, which requires very long jaws, large unshielded volumes, abrupt steps, and a dielectric material as absorber, did not make it easy to reduce the impedance at the design stage and still represent an issue for the new TDIs that are being designed for installation during LS2.

Significant effort was invested in modifications and studies during LS1 to improve the situation [4]: more pumping power was installed [7], the beam screen was stiffened (stainless steel instead of copper with the addition of more supports), the jaw mechanism was refurbished, the copper coating was removed from the beam screen (which reduces the shunt impedance from the resonant modes). In addition, temperature probes could finally be added on the lower jaw (4) on the support (2), and on the beam screen (2), but despite a lot of effort by EN-STI and TE-VSC, the copper coating on the jaw could not be implemented due to an unforeseen issue with the integrity of the sandwich of coating layers [4]. As a consequence, the heat load to the TDI jaw is expected to be unchanged for Run 2 and it cannot be excluded that heating issues come back after LS1. However, the refurbished TDIs should cope better with this heat load and they should be monitored closely after LS1. It is in particular recommended that the time spent with the TDI jaw gap closed when high intensity beams circulate in the machine should be minimized: ideally the TDI should be opened after each injection when the circulating beam intensity becomes significant and a trade-off should be found with the mechanical reliability and the machine availability.

If heating problems come back, the additional diagnostics and the TDI8 impedance measurements before installation should indicate the best mitigation mechanism (bunch length increase or bunch shape change, bunch intensity decrease or total intensity decrease). Besides, new spares with copper coating - among other improvements - are planned to be installed during the Christmas stop 2015/2016.

Synchrotron Light Monitor BSRT

In 2012, the BSRT mirror system was damaged by proton beam induced RF heating. Significant increase of temperature was observed, as well as deformation of the mirror - that affected the transverse emittance measurement - and damage on the mirror holder and ferrite, which were worrying for machine protection.

These problems were linked to the difficulty of evacuating the heat from the ferrite that was placed to damp a large RF mode generated by the mirror and mirror holder. During LS1, the mirror and mirror holder geometries were modified to attenuate the RF mode (see Fig. 1). The metallic holder that was acting as an antenna was removed and the first RF mode is now expected to be small enough so that no ferrite needs to be installed. RF measurements and simulations were performed to validate the design, and simulations currently predict 50 to 200 W on the whole device in case the mode is excited by the 40 MHz beam frequencies (only 1 to 8 W would heat the mirror in that case, since the rest would heat the copper coated surroundings), while before LS1 almost all of the 30 W were continuously heating the ferrite ring. It is crucial to note that the removal of the ferrite turned the mode from broadband to narrow band, and changed the probability to hit a beam spectrum line from 100% before LS1 to an order of 0.1% (considering that the first RF mode would have a width of 40 kHz in a comb of sharp 40-MHz-spaced exciting beam frequencies).

In case these heating problems come back after LS1, the beam intensities and bunch lengths can be optimized. The vacuum chamber could also be cooled from the outside since a large proportion of the heat should be dissipated in the copper coated vacuum pipe. Slightly moving the mirror holder to try and avoid overlapping of the sharp RF mode with the sharp beam frequencies could also be tried (if mechanically possible after installation).

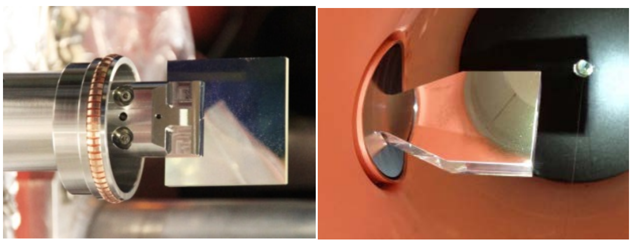

Figure 1: BSRT design installed before LS1 (left) and after LS1 (right) (courtesy BE-BI).

Roman pots

The temperature of the ATLAS-ALFA detectors inside the Roman pots got very close to the damage limit in September-October 2012 [14], while Cryo regulation issues on neighbouring Q6R5 could have been caused by heating/outgassing on one of the neighbouring TOTEM Roman pots XRPH.A6R5.B1. In fact, evidence of overheating of the ferrites was found during LS1 and they turned out to be damaged [15]. Since it was efficiently cooled, the TOTEM detector was not threatened to be damaged.

Also in this case, significant redesign of the Roman pots was launched before LS1 to reduce beam induced heating and the ferrites were relocated where they can be cooled more easily (see Fig. 2). For ATLAS-ALFA, heat extraction and cooling capacity was also improved [16].

If heating problems come back, the cooling capacity from the outside can be increased (e.g. fans or water cooling), and the Roman pots should be kept far from the high intensity beams.

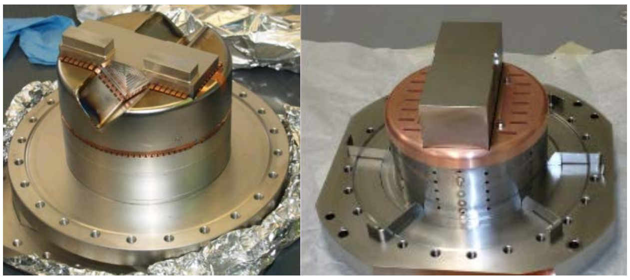

Figure 2: Shielding of ATLAS-ALFA (left) and consolidated TOTEM (right) roman pots installed during LS1 to improve the impedance (courtesy ATLAS-ALFA and TOTEM).

Injection kickers MKI

The screen conductors allow the shielding of the ferrite from the beam and thereby reduce the longitudinal impedance and the related heating. For all the MKIs installed pre-LS1, 9 screen conductors (out of 24) were not installed to avoid electrical breakdowns. Before LS1, the temperature of all injection kickers was increasing with beam in the LHC. However, prior to Technical Stop 3 (TS3) in 2012 the temperature of one injection kicker in particular (MKI8D) approached the Curie temperature of the ferrite, which was measured to start to affect the kicker performance [10]. Therefore, on several occasions prior to TS3, one had to wait after a fill that the temperature of this MKI8D decreased below the SIS threshold before taking new injections from the SPS. This MKI8D was exchanged during TS3 2012. Finally, when the MKI8D was inspected the 15 screen conductors were found to be twisted by 90 degrees, from one end to the other, and hence were not screening the ferrite efficiently.

Results of pre-LS1 studies to redesign the screen conductors (now staggered and without metallization around the ceramic at the end), were implemented during LS1 on all injection kickers so that all 24 screen conductors could be installed. The situation with respect to heating is therefore expected to be much more favourable than before LS1 and heating is not expected to be a problem during run 2. Besides, the impedance of all MKIs was systematically measured before reinstallation for Run 2 and no non-conformities were detected. In addition to upgrading the beam screen, treatment of the inside of the MKI tanks, to improve radiative cooling of the ferrite, was tested but was not successful: other studies to improve future cooling are ongoing.

Although heating of the MKIs is not expected to be a problem, during run 2, SoftStarts will continue to be carried out, following a physics run, to refine and validate the SIS temperature interlocks after LS1. Before LS1 (with 50 ns beam), the decrease of the intensity per bunch and the increase of bunch length were efficient knobs to mitigate beam induced heating.

It can finally be noted that the three systems, for which the temperature increase led to increase the bunch length from 1ns to 1.25 ns in 2011, were better controlled (Cryo) upgraded (MKIs) or removed (TCTVBs). There is therefore in principle no known showstopper to reduce the bunch length closer to nominal bunch length after LS1, as a dedicated operational test at injection with 50 ns beam indicated in 2012 [3]. However, it cannot be guaranteed that all systems - by design or following non-conformities - will not limit the bunch length reduction for a given beam intensity.

IMPACT OF HARDWARE CHANGES ON BEAM STABILITY

This chapter covers the changes that are expected to have the largest impact on beam stability after LS1: new collimators with BPMs and ferrites, and Roman pots/TCL6 insertions during high luminosity fills.

New collimators with BPMs and ferrites

A new proposal of tertiary collimators with embedded BPMs made the design of the lateral RF contacts difficult. At the request of the collimation project team and following the issues with RF contacts that occurred in 2011, the impedance team recommended in 2011 to leave the gap open and install ferrites (only for the 8 TCTPs and 1 TCSG in 6 per beam, provided the gap is not too small).

Following new benchmarks with simulation tools that became available in the meantime, it was realized that a transverse RF mode at around 100 MHz enhanced by the large beta function at these tertiary collimators was not damped enough by the ferrite (contrary to the other modes at higher frequencies) and was emerging out of the current LHC impedance model (see Fig. 3) [17, 18]. These impedance simulations were later confirmed by impedance measurements [19]. The codes DELPHI and HEADTAIL [20], as well as NHTVS [22] expected a small impact on beam stability of this additional “TCTP mode” (see for instance DELPHI results in Fig. 4).

Besides, following the issues with ferrites heating on other LHC equipment, it was checked that most of the beam induced heat load occur on the jaw and not on the ferrites (~1 W expected on the ferrites after LS1).

In case problems occur, it is again crucial to check if it is linked to a non-conformity or to a design problem to decide if useful to exchange with spare(s). For stability, the jaw gap could be increased, or at constant gap the beta function at the TCTs could be decreased (if possible and desirable since this would require increasing β*). For heating, increasing bunch length and decreasing jaw gap should help. For both collective effects, decreasing bunch intensity would help.

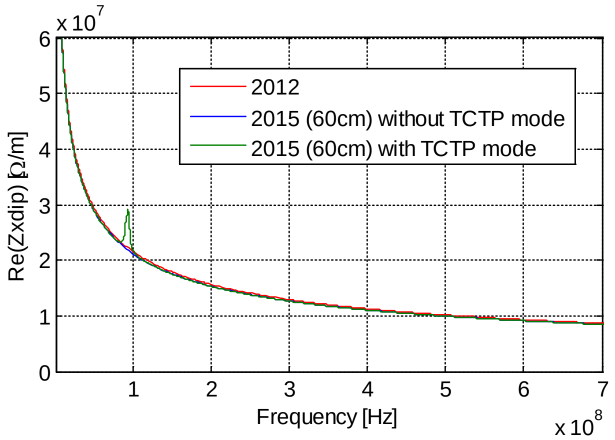

Figure 3: Impact of the 100 MHz mode of the 8 TCTP and 1 TCSG per beam on the real part of the horizontal impedance of the current LHC model for β*=60 cm (in green), compared to the case without this “TCTP mode” (in blue) and to the 2012 impedance model (in red).

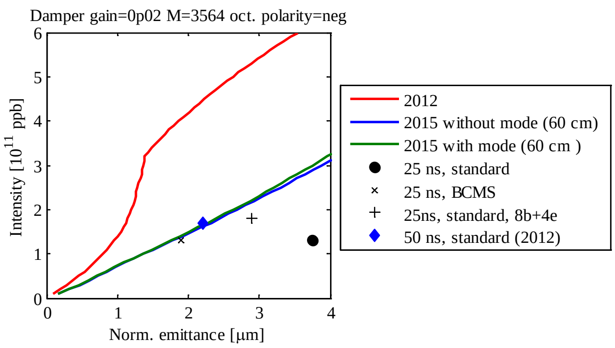

Figure 4: Impact of the 100 MHz mode of the 8 TCTP and 1 TCSG per beam on the stability limit as computed by the DELPHI code for a filled LHC with 25 ns bunch spacing, negative octupole polarity and β*=60 cm (in green), compared to the case without this “TCTP mode” (in blue) and to the 2012 case (in red). The beam is stable below the lines, unstable above the lines. The large difference between 2012 and 2015 is the result of the change of beam energy.

Finally, following these studies, the recommendation from impedance point of view for future designs of collimators with embedded BPMs would now be to use lateral RF contacts instead of/in addition to the ferrites to completely avoid these potential issues. However the operational experience with these new TCTPs after LS1 will allow assessing whether the predictions that these issues have a small impact on heating and stability are confirmed.

New TCL4, TCL6 collimators and Roman pots operation during high luminosity physics fills

Proposals for operational scenarios for Run 2 foresee very small gaps for Roman pots and TCL6 in IP5 due to the very low horizontal beta function at this location, which would lead to significant impedance [22]. TCL6 settings should therefore be optimized taking impedance into account. On the other hand, the newly installed TCL4 is predicted to have a smaller impact (metallic collimator at standard gaps).

The operational scenarios for these collimators and Roman pots are planned to be discussed at the collimation working group, LHCC and LMC, and a tradeoff should eventually be found between (1) TOTEM protection and performance and (2) the requirements by the impedance, energy deposition, collimation and machine protection teams.

It is important to note that these components should only move in with colliding beams, which means that stability issues are expected to be less critical thanks to the large landau damping provided by the head-on beam-beam effect. However heating issues would not be reduced unless these insertions are performed later in the fill when the intensity per bunch decreases and the stabilization of the bunch shape can significantly reduce the heating.

In case there are problems after LS1 when inserting the Roman pots and or TCL6, the solution will be straightforward: keep the Roman pots and associated TCL6 retracted until the collective effects have reduced enough during the fill.

OTHER RELEVANT CHANGES

Additional modifications are worth mentioning:

- A third TCDQ module was added but the simulated impact on impedance is expected to be small [23].
- No impact is expected from the additional passive absorbers in IR3 [24].
- The installation of the new BGV was carefully followed up by the impedance team and potential heating by RF mode at high frequency should be monitored. Cooling has been foreseen by the BE-BI team [25].
- A goniometer for UA9 was installed to be used during MDs but no impact is expected since it was designed to be efficiently screened from the beam during regular operation. Impedance measurements confirmed the efficiency of this screening [26].
- No issue is expected from the new beam pipe with lower aperture installed in CMS and ATLAS [27].

Besides, it can be noted that the 8b+4e beam, which could replace the 25 ns beam in case electron cloud is an issue, may lead to more heating for some equipment than the standard 25 or 50 ns beam due to the additional beam spectral lines that are not present with either regular 50 ns or 25 ns beams.

Finally, new studies account for the impact of 2 counter-rotating beams on beam induced heating in the beam screen (with weld). The coupling of the two beams seems small so far from power loss point of view: 2 beams in the same aperture are not too different from 2 beams in distinct apertures [28].

STATUS OF BEAM INDUCED RF HEATING ISSUES

The following tables summarize the status of the beam induced heating issues before and after LS1.

Table 1: list of devices affected by beam induced heating before LS1 and expectations for 2015 (black means that equipment was damaged, red means that operation was limited due to equipment at some point, yellow means that operation required close follow up, green means that the problem was thought to be solved).

Element	Problem	2011	2012	2015 (expected)
VMTSA	Damage	black	green	All removed (green)
TDI	Damage	black	black	Refurbished (yellow)
MKI	Delay (cooldown)	red	red	Upgraded (green)
TCP B6L7 On beam 1	Few dumps	red	red	Exchanged (green)
TCTVB	Few dumps	yellow	yellow	Removed (green)
Q6R5	Regulation at the limit	yellow	green	Valves upgraded Neighboring TOTEM pot upgraded (green)
ATLAS-ALFA	Damage risk	yellow	red	New design installed (yellow)
BSRT	Damaged	yellow	black	New design installed (yellow)

Table 2 shows the summary of expected heat load from interaction of the impedance before LS1 (1374 bunches with 1.7 10^{11} p/b, with 4 sigma bunch length of 1.25 ns), after LS1 (2748 bunches with 1.2 10^{11} p/b, with 4 sigma bunch length of 1.25 ns) and after LS1 in case the bunch length is reduced to 1 ns. It can be concluded that significant improvements are expected after LS1 with the consolidation of many devices. These improvements are planned to be carefully monitored during Run 2 thanks to the many temperature probes that were added during LS1.

Element	Before LS1	After LS1 (1.25 ns)	After LS1 (1 ns)
TDI*	36 W	36 W (~)	48 W (+33%)
Arc beam screens	186 mW/m	215 mW/m (+15%)	300 mW/m (+60%)
Triplet beam screens (Q1/Q2-Q3)	286/360 mW/m	331/419 mW/m (+15%)	460/590 mW/m (+60%)
MKI	70 W/m† 160 W/m‡	20-40 W/m	36-55 W/m
MKD	22 W	22 W (~)	30 W (+35%)
TCP collimator	62 W	60 W (~)	92 W (+48%)
TCTP (at +/-5 mm)	-	3 W	5 W
TOTEM** at 40 mm at 2 mm	10 W 57 W	5 W (-50%) 10W(-80%)	13 W (+30%) 27 W (-32%)
ATLAS-ALFA at 40 mm	37 W	7 W (-80%)	20 W (-45%)
BSRT mirror broadband narrowband	30 W 0 W	1 W 1 to 4 W§	4 W 2 to 8 W§
BGV**	-	50 W§	1 kW§
ALICE cone** CMS cone** LHCb cone**	200 W§ 55 W§ 50 W§	400 W§ 110 W§ 100 W§	640 W§ 300 W§ 190 W§

STATUS OF SINGLE BEAM STABILITY

Margin was expected and measured in the longitudinal plane and lower longitudinal emittances/bunch length after LS1 could be feasible, if interesting for the experiments [3].

Concerning transverse impedance related single beam stability, the current impedance model expects that the nominal 25 ns beam (2808 bunches with 1.15 10^{11} p/b within 3.75 mm.mrad norm. transverse emittance) would be stable at 6.5 TeV and β*=65 cm with octupole polarities powered to their maximum positive or negative current, high chromaticity and maximum ADT gain [29]. In the frame of these assumptions, the stability limit for this beam would be expected at ~1.3 10^{11} p/b within ~2.8 mm.mrad norm. transverse emittance.

* Resistive wall of the TDI jaws retracted to 55 mm

† For conform MKIs with 15 screen conductors

‡ For non-conforming MKI8D pre TS3 2012

§ Potential heat load (if interacts with beam spectral line)

** Main mode

CONCLUSION

Following the significant impedance related issues during Run 1, the effort by all involved equipment groups to assess and reduce impedance is expected to pay off, so that most beam induced RF heating issues should be solved. Concerning the global LHC impedance, the hardware changes are expected to be transparent. However, heating and stability diagnostics and their continuous monitoring will be crucial after LS1 to diagnose and mitigate potential unexpected issues.

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