CERN-ACC-NOTE-2020-0033 MD

June 19, 2020

david.amorim@cern.ch

MD3318 – Impedance Contribution of Secondary and Tertiary Collimators

D. Amorim / BE-ABP, S. Antipov / BE-ABP, N. Biancacci / BE-ABP, X. Buffat / BE-ABP, A. Mereghetti / BE-ABP, E. Métral / BE-ABP, S. Redaelli / BE-ABP, B. Salvant / BE-ABP, M. Soderen / BE-RF, D. Valuch / BE-RF

Keywords: LHC, secondary collimator, tertiary collimator, impedance

---

Summary

This report summarises the results of MD3318 about impedance measurements of individual LHC secondary and tertiary collimators. The measurements took place during the MD block III of 2018, on the afternoon of the 27th of October. Individual collimators impedance can be estimated from the tune shift induced by the collimator gap variation. The transverse damper was set-up to coherently excite the beam, and its oscillations were recorded with the ADT ObsBox, as done in previous MD activities. The beam was excited in quick successions, while varying the collimator gap, to mitigate the effect of tune drift and tune jitter. This method allows to measure tune shifts in the order of a few 10^{-5}.

---

1 Introduction

At the top energy of 6.5 TeV the LHC collimation system is responsible for a sizeable fraction of the LHC beam coupling impedance budget [1]. In order to accommodate increasingly smaller values of β^*, the LHC operational settings of the collimators must be tightened increasing in turn their contribution to the overall machine impedance budget. Moreover, brighter beams, as foreseen for the High Luminosity LHC project [2], will be more prone to impedance induced destabilising effects.

In this context, it is therefore important to accurately quantify the contribution of individual collimators to the LHC impedance. Models of the machine impedance and numerical simulations are fundamental predictive tools for coherent beam stability. It is therefore essential to benchmark simulation results against accurate measurements with beam, either involving entire families of collimators or selected ones.

Past MD activities (i.e. MD314 [3] in 2015, MD1447 [4] in 2016) were aimed at evaluating the impact on impedance from all the IR7 secondary (TCSG) collimators at 6.5 TeV. The measurement method was further refined to allow for individual collimators impedance measurements, such as in MD1446 [5] or MD1875 [6].

The present MD goal is to measure the individual contribution to the impedance of a selected set of IR7 secondary collimators (TCSG), as well as the IR2 tertiary collimators. The TCSG collimators are the largest contributors to the overall collimators impedance at top energy. This is caused by their physical proximity to the beam, the low electrical conductivity of the jaw material (CFC), their number and their total length. For the High Luminosity LHC project, an upgrade of the LHC collimators is foreseen. The current secondary collimators in the betatron cleaning insertion (IR7) will be upgraded to low resistivity collimators made of a Molybdenum-Graphite bulk coated with Molybdenum. During the Long Shutdown 2 (LS2), four secondary collimators of IR7 will be upgraded to low resistivity collimators. One of the MD goal was to measure the tune shifts induced by the collimators currently installed to be able to compare to the low impedance one after LS2. The TCSG measured during the MD activity are the ones targeted by the LS2 collimation upgrade [7].

The second goal of the MD was to measure the tune shifts induced by tertiary collimators (TCT). These collimators are made of tungsten, a better electrical conductor, and are placed upstream of the Interaction Points (IPs) and thus have a large gap because of the larger beta functions. The tune shifts induced by these collimators are thus expected to be small. Among all tertiary collimators, those of IR2 have been chosen. The beam size in these collimators is the smallest among TCTs. Therefore the physical gaps of the collimators will be smaller, increasing the induced tune-shift.

The third goal of the MD was to measure the tune shifts induced by the TCSPM. The TCSPM is a low resisitiy collimator prototype, with Molybdenum-Graphite (MoGr) jaws coated alongisde with two stripes of different materials: Molybdenum (Mo) and Titanium-Nitride (TiN) [8]. This collimator was installed during the 2016/2017 Extended Year End Technical Stop (EYETS), and its impedance was already measured in 2017 [9]. The MD re-performed the measurement to assess the effect of one year of beam exposure on the jaws.

Moreover, as the TCSPM activity took place on B2, two of the B1 primary collimators (TCP) have also been measured. The results will be compared to past measurements carried on the TCP during MD1446.

2 Procedure and Beam Conditions

To evaluate the impedance of single collimators, the beam tune shift was measured while varying the gap of the selected collimators. The list of collimators measured is presented in Tab. 1. The expected tune shifts caused by single collimators is smaller than the BBQ resolution. To resolve the tune shifts, the procedure tested in MD1447 [4] was used. This method employs the transverse damper (ADT) as an exciter to coherently kick the beam [10]. This allows for a fine control of the kick excitation in terms of amplitude, time profile and bunch selection. The turn-by-turn data were automatically recorded with the ADT ObsBox [11] each time an excitation was applied.

This technique was further refined during MD2191 [12]: for this MD the tune shifts measured were in the order of a few 10^{-5}. To obtain this resolution, the beam was kicked in fast succession with the ADT while quickly cycling the collimator gap between the upper and lower positions. This allowed to mitigate the effects of tune drift and tune jitter observed in previous MD activities [13].

The MD activity was carried out on the 27^{th} October 2018, between 14h and 19h30 [14, 15]. The 6.5 TeV flat-top optics were used, at the end of the "ramp and squeeze" beam process. In this configuration, the β^* remains at 3 m in IP1/5, and the beams are kept separated in the

Table 1: Collimators measured during the MD.

Family	B1	B2
IR7 TCSGs	TCSG.D4L7	TCSG.D4R7
	TCSG.B4L7	TCSG.B4R7
	TCSG.E5R7	TCSG.E5L7
	TCSG.6R7	TCSG.6L7
IR2 TCTs	TCTPH.4L2	TCTPH.4R2
	TCTPV.4L2	TCTPV.4R2
TCSPM	-	TCSPM.D4R7, Mo stripe
	-	TCSPM.D4R7, MoGr stripe
	-	TCSPM.D4R7, TiN stripe
IR7 TCP	TCP.C6L7	-
	TCP.D6L7	-

IPs.

Figure 1 shows an overview of the main activities carried out during the MD. After injection, the beams were brought to top energy. A careful set-up of the ADT and the beam parameters was performed to obtain clear kick signals without noticeable beam losses. The negligible beam losses and emittance blow-up allowed to perform the full MD program while maintaining an almost constant brightness. Emittances were at ∼1.8 µm in the horizontal plane and ∼1.5 µm in the vertical plane for both beams.

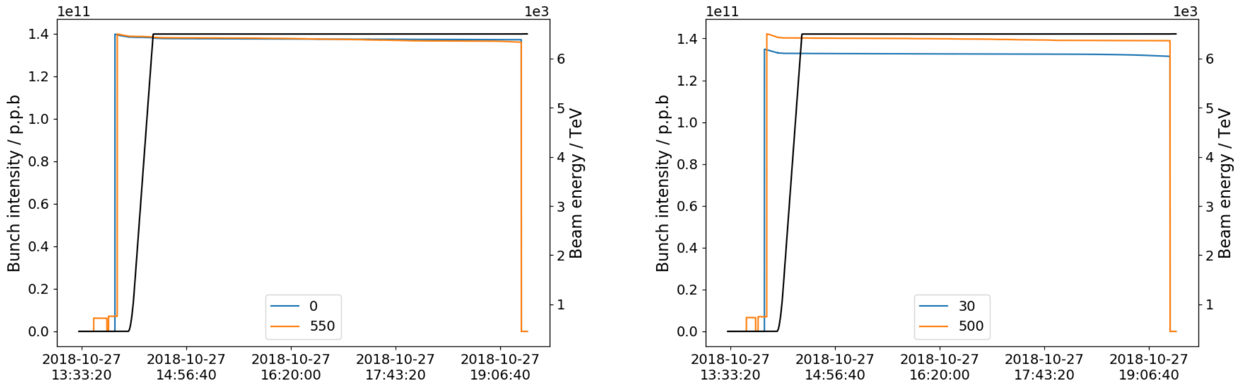
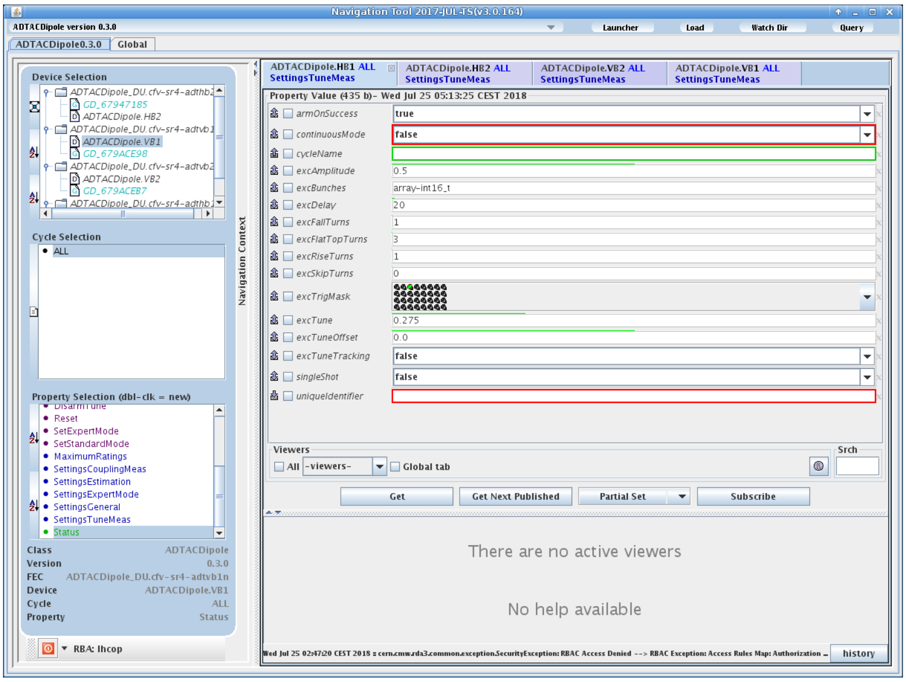


Figure 1: B1 (left) and B2 (right) overview of the MD activity. The coloured curves represent the bunch intensity, with their bunch number in legend. The black curves represent the beam energy. Intensity losses were negligible throughout the MD activity.

The detailed program of the MD was:

- a first set-up of the ADT was performed with the previous MD beam. The strength, excitation rise/fall time, and kick duration were set-up in the FESA class as shown in Fig. 2. The bunch number and the excitation command were sent using a Python script using the PyJAPC library [16]. The MD beam was then injected, using the `Single_20b_0_0_0_Instabilities` filling scheme, shown in Fig. 3.

  In each beam two nominal bunches of 1.3×10^{11} protons per bunch were injected.



Class ADTACDipole
Version 0.3.0
FEC ADTACDipole_DU.cfv-sr4-adtvb1n
Device ADTACDipole.VB1
Cycle ALL
Property Status

Property Value (435 b)- Wed Jul 25 05:13:25 CEST 2018

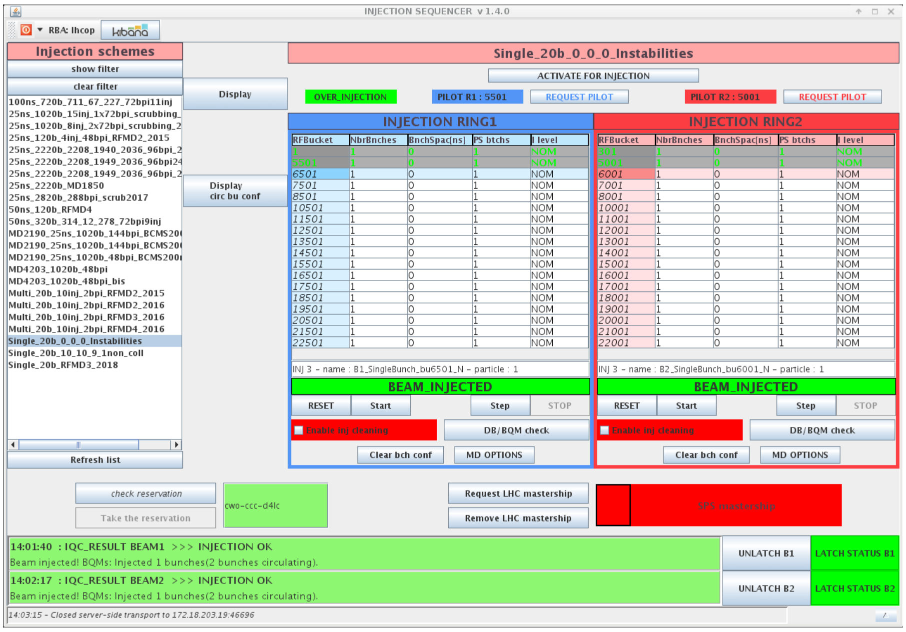
armOnSuccess: true
continuousMode: false
cycleName:
excAmplitude: 0.5
excBunches: array-int16_t
excDelay: 20
excFallTurns: 1
excFlatTopTurns: 3
excRiseTurns: 1
excSkipTurns: 0
excTrigMask:
excTune: 0.275
excTuneOffset: 0.0
excTuneTracking: false
singleShot: false
uniqueIdentifier:

There are no active viewers

No help available

Wed Jul 25 02:47:20 CEST 2018 : cern.cmw.rda3.common.exception.SecurityException: RBAC Access Denied --> RBAC Exception: Access Rules Map: Authorization …

Figure 2: FESA class setup used for the MD. The parameters were kept identical to previous similar MD activities.



100ns_720b_711_67_227_72bpi11inj
25ns_1020b_15inj_1x72bpi_scrubbing_
25ns_1020b_8inj_2x72bpi_scrubbing_2
25ns_120b_4inj_48bpi_RFMD2_2015
25ns_2220b_2208_1940_2036_96bpi_2
25ns_2220b_2208_1949_2036_96bpi24
25ns_2220b_2208_1949_2036_96bpi_2
25ns_2220b_MD1850
25ns_2820b_288bpi_scrub2017
50ns_120b_RFMD4
50ns_320b_314_12_278_72bpi9inj
MD2190_25ns_1020b_144bpi_BCMS20
MD2190_25ns_1020b_144bpi_BCMS20
MD2190_25ns_1020b_48bpi_BCMS200
MD4203_1020b_48bpi
MD4203_1020b_48bpi_bis
Multi_20b_10inj_2bpi_RFMD2_2015
Multi_20b_10inj_2bpi_RFMD2_2016
Multi_20b_10inj_2bpi_RFMD3_2016
Multi_20b_10inj_2bpi_RFMD4_2016
Single_20b_0_0_0_Instabilities
Single_20b_10_10_9_1non_coll
Single_20b_RFMD3_2018

Single_20b_0_0_0_Instabilities

PILOT R1 : 5501

PILOT R2 : 5001

INJECTION RING1

RFBucket	NbrBnches	BnchSpac[ns]	PS btchs	I level
1	1	0	1	NOM
5501	1	0	1	NOM
6501	1	0	1	NOM
7501	1	0	1	NOM
8501	1	0	1	NOM
10501	1	0	1	NOM
11501	1	0	1	NOM
12501	1	0	1	NOM
13501	1	0	1	NOM
14501	1	0	1	NOM
15501	1	0	1	NOM
16501	1	0	1	NOM
17501	1	0	1	NOM
18501	1	0	1	NOM
19501	1	0	1	NOM
20501	1	0	1	NOM
21501	1	0	1	NOM
22501	1	0	1	NOM

INJ 3 - name : B1_SingleBunch_bu6501_N - particle : 1

INJECTION RING2

RFBucket	NbrBnches	BnchSpac[ns]	PS btchs	I level
301	1	0	1	NOM
5001	1	0	1	NOM
6001	1	0	1	NOM
7001	1	0	1	NOM
8001	1	0	1	NOM
10001	1	0	1	NOM
11001	1	0	1	NOM
12001	1	0	1	NOM
13001	1	0	1	NOM
14001	1	0	1	NOM
15001	1	0	1	NOM
16001	1	0	1	NOM
17001	1	0	1	NOM
18001	1	0	1	NOM
19001	1	0	1	NOM
20001	1	0	1	NOM
21001	1	0	1	NOM
22001	1	0	1	NOM

INJ 3 - name : B2_SingleBunch_bu6001_N - particle : 1

cwo-ccc-d4lc

```
14:01:40  : IQC_RESULT BEAM1  >>> INJECTION OK
Beam injected! BQMs: Injected 1 bunches(2 bunches circulating).
14:02:17  : IQC_RESULT BEAM2  >>> INJECTION OK
Beam injected! BQMs: Injected 1 bunches(2 bunches circulating).
14:03:15 - Closed server-side transport to 172.18.203.19:46696
```

Figure 3: Filling scheme used for the MD. This scheme can host up to twenty bunches per beam, ensuring neither bunch collisions nor long range interactions between the two counter-rotating beams. Only the two first bunches in the scheme were injected for the MD (highlighted in green). The second bunch was not kicked so to be used as a spare in case of large intensity losses on the first bunch.

- the beams were ramped to flat-top with full octupoles current (564 A). Chromaticity was then reduced from the operational 15 units to 7 units for both beams and planes, in two steps of -5 and -3 units.
- the ADT gain was then reduced by a factor of 2 in the trim editor. The blow-up gain was also reduced from 0.04 to 0.035 in the trim editor. An example of a kick signal is shown

in Fig. 4.

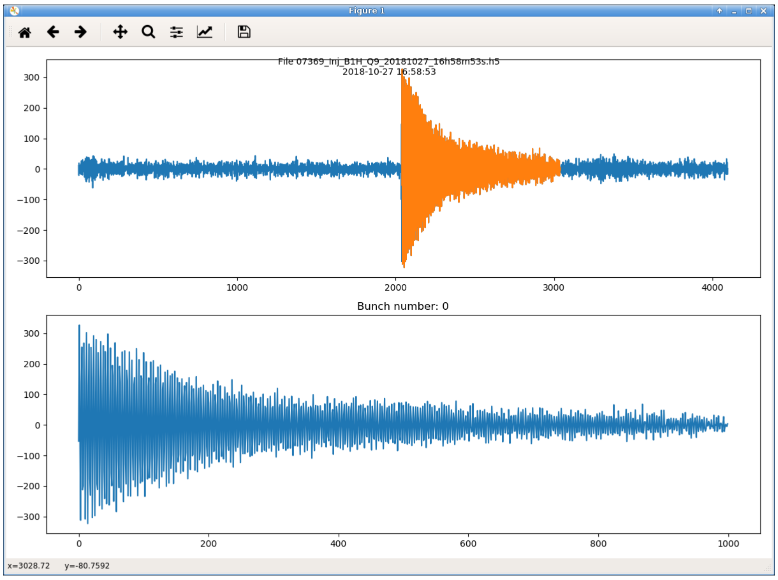


Figure 4: Example of a kick signal for B1H. The top plot shows the full turn-by-turn bunch position data recorded by the ADT ObsBox. The bottom plot shows the data selected for the tune reconstruction.

- the gaps of the collimators to be measured were then cycled in quick successions while kicking the beam with the ADT and recording the data with the ADT ObsBox. The procedure can be visualised in Fig. 5. The collimators settings are reported in Tab. 2.

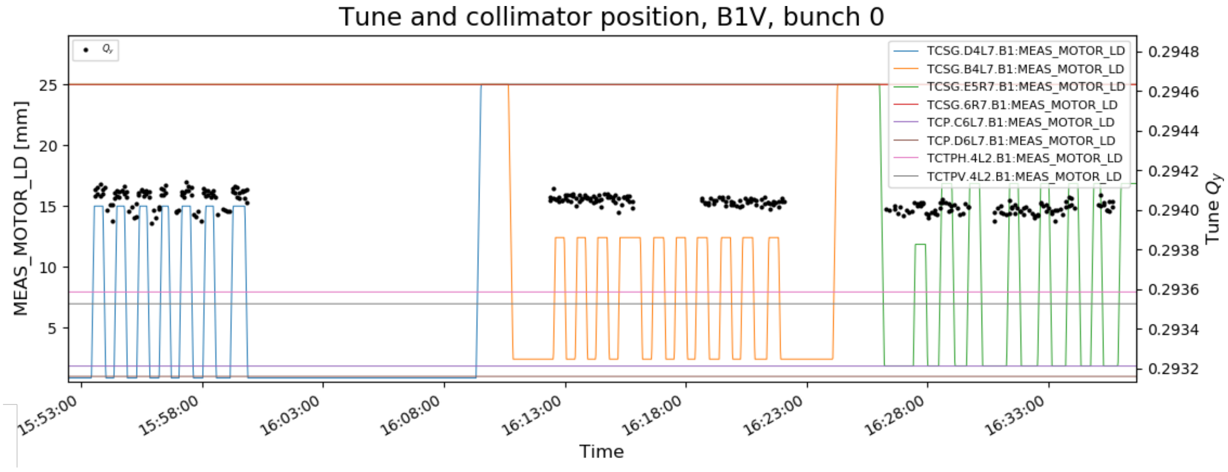


Figure 5: Collimators position versus time during the measurement of three collimators. The solid curves denote the collimator gap of TCSG.D4L7 (blue curve), TCSG.B4L7 (orange curve) and TCSG.E5R7 (green curve). The dots show the vertical tune computed from the kick signals. A tune shift is clearly visible for the TCSG.D4L7 (a vertical collimator), and a smaller shift is also visible for the TCSG.E5R7 (a skew collimator).

- a further chromaticity reduction by 2 units in the horizontal plane of both beams took place. The chromaticity should have thus been 5/7 units in H/V for both beams. A reduction of the octupole current to 370 A was also performed.

Table 2: Collimators gaps set-up during the measurements. The second column gives the half-gap in mm. The first value corresponds to the half-gap when the collimator is closed. The second value is the value set to open the collimator. The third column gives the collimator gap in LHC collimation beam size $\sigma_{coll} = \frac{1}{\sqrt{\gamma}}\sqrt{\beta_x \varepsilon_{coll} \cos^2\theta + \beta_y \varepsilon_{coll} \sin^2\theta}$, where γ is the beam Lorentz factor, $\beta_{x,y}$ are the betatron values at the collimator location, θ is the collimator azimuthal angle and $\varepsilon_{coll} = 3.5\,\mu\text{m}$ is the LHC nominal normalised emittance.

Family	Half-gap / mm	Setting / σ_{coll}
TCSG.D4L7.B1	1.12 + 15	6
TCSG.D4R7.B2	1.12 + 15	6
TCSG.B4L7.B1	1.60 + 10	6
TCSG.B4R7.B2	1.66 + 10	6
TCSG.E5R7.B1	1.81 + 15	6
TCSG.E5L7.B2	1.81 + 15	6
TCSG.6R7.B1	2.47 + 15	6
TCSG.6L7.B1	2.47 + 15	6
TCTPH.4L2.B1	1.24 + 10	6
TCTPH.4R2.B2	1.24 + 10	6
TCTPV.4L2.B1	1.37 + 15	6
TCTPV.4R2.B2	1.37 + 15	6
TCSPM.D4R7.B2, MoGr stripe	1.09 + 10	6
	1.00 + 10	5.5
	0.95 + 10	5.2
	0.91 + 10	5
	0.87 + 10	4.8
TCSPM.D4R7.B2, Mo stripe	0.87 + 10	4.8
	0.91 + 10	5
	0.95 + 10	5.2
	1.00 + 10	5.5
	1.09 + 10	6
TCSPM.D4R7.B2, TiN stripe	1.09 + 10	6
	0.91 + 10	5
TCP.C6L7.B1	1.38 + 10	5
TCP.D6L7.B1	0.89 + 10	5

3 Results of Impedance Measurements

The turn-by-turn transverse position of each excited bunch recorded by the ADT ObsBox was used to compute the tune. The individual tune for each bunch was obtained using harmonic analysis, specifically the Harpy code [17]. The data of the first 500 turns after the bunch excitation were used, which corresponds to the transverse oscillation decoherence time.

The measurement results were compared to predictions obtained from ImpedanceWake2D [18] and Sacherer's formula, accounting for both the driving and detuning impedance induced by collimators.

Figures 6 and 7 show the results obtained for Beam 1, both horizontal and vertical planes.

It is notable that in 4 out of 8 cases the measured tune shift turned out to be significantly, up to 100%, larger than expected. This is the case for the secondary collimators B4L7 and 6R7, in the horizontal plane, and D4L7 and E5R7 in the vertical plane. The primary C6L7 (horizontal) is particularly under-estimated (factor 3 higher tune shift than expected), while the D6L7 (vertical) is close to the model within 10-20%.

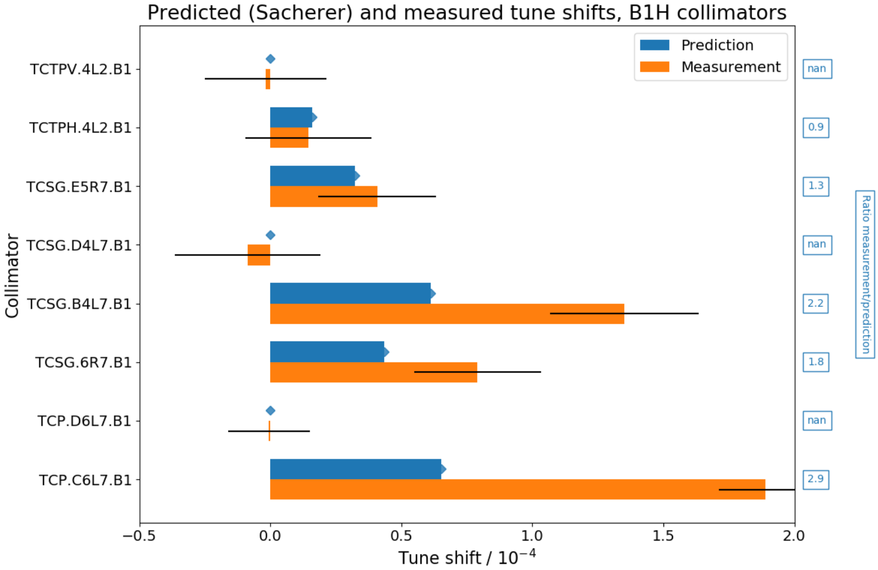


Figure 6: Measured tune shift in the horizontal plane of Beam 1 (orange) compared to predictions from the LHC impedance model (blue). The ratio between the measurement and prediction is reported alongside the plot.

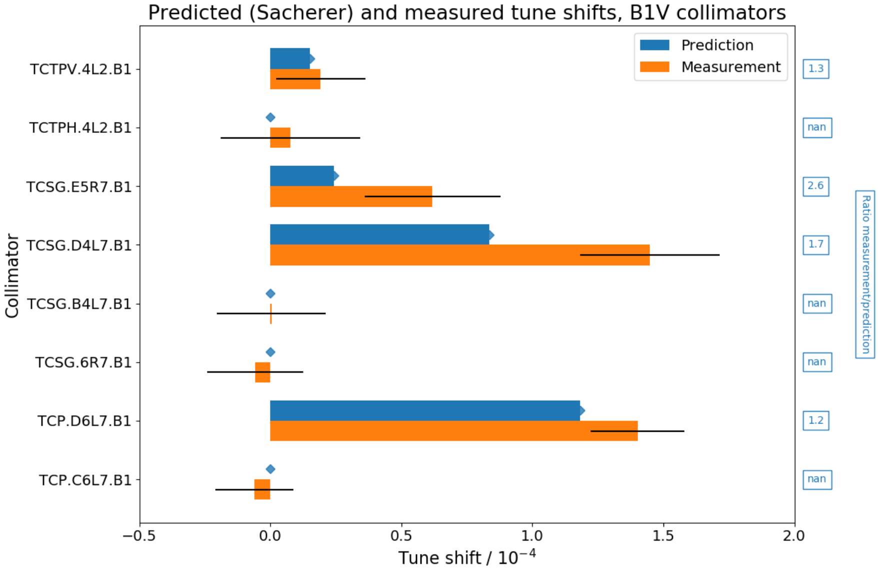


Figure 7: Measured tune shift in the vertical plane of Beam 1 (orange) compared to predictions from the LHC impedance model (blue). The ratio between the measurement and prediction is reported alongside the plot.

Figure 8 shows the results of the different measurements performed on Beam 2 collimators during the LHC Run II, including those obtained during this activity. Most of the measured tune shifts agree with the predictions with their respective error bars with the only exception being the latest measurement of the D4R7 collimator, which induces a larger shift than expected in 2018. It is worth noting that 4 previous measurements of the same collimator taken in 2017 agree with their predictions. The discrepancy could either be related to the deterioration of jaw conductivity or to the potential beam misalignment with respect to the jaw during the last test. More systematic measurement data is needed to investigate the issue further and conclude on the reason of this discrepancy.

Results for the horizontal plane of Beam 2 are missing due to an ADT ObsBox issue which stopped the data recording for this specific beam and plane.

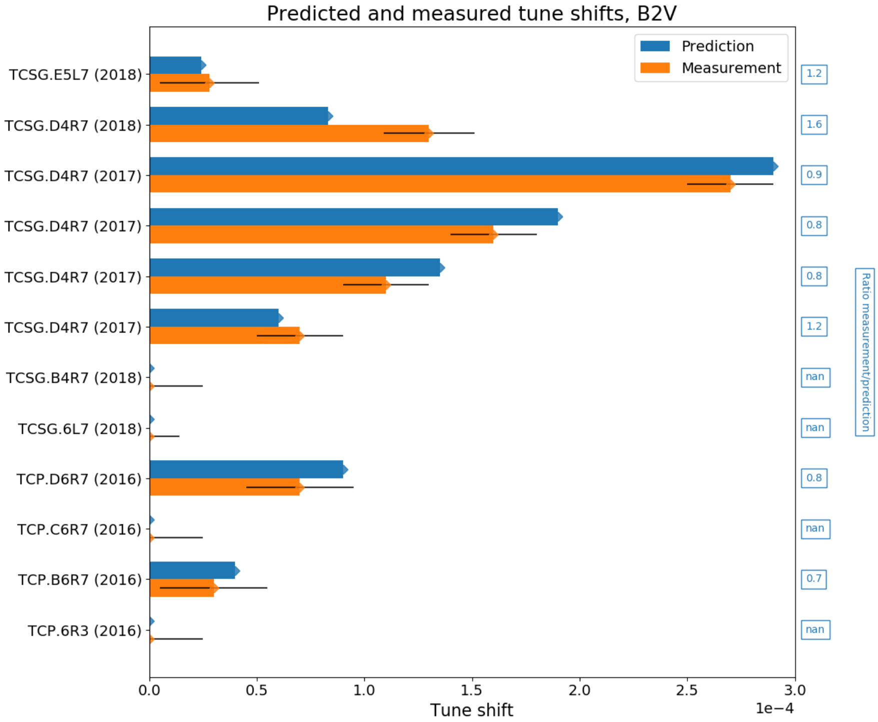


Figure 8: Measured tune shift in the vertical plane of beam 2 (orange) compared to predictions from the LHC impedance model (blue). The results of the different measurement performed during LHC Run II are shown. The ratio between the measurement and prediction is reported alongside the plot.

For the tertiary collimators, Figs. 6 and 7 show that their contributions are below the resolution limit of the measurement method, which confirms the hypothesis that they have negligible contributions with respect to the IR7 collimators.

The MD allowed also to re-measure the tune shift of the TCSPM collimator as a function of the collimator half gap. Figure 9 summarizes the results [19]: the tune shift of the 2018 data (squares) is increased by a factor of about 2 with respect to the 2017 data (circles). Possible reasons for the increment could be related to collimator misalignment and/or jaw resistivity degradation due to radiation. These aspects are under investigation and will be subject of dedicated MDs during the LHC Run 3.

4 Conclusions

First, the measurement of tune shifts induced by tertiary collimators reached the resolution limit of the measurement method of $\sim 2 \times 10^{-5}$. The obtained tune shift values below 5×10^{-5}

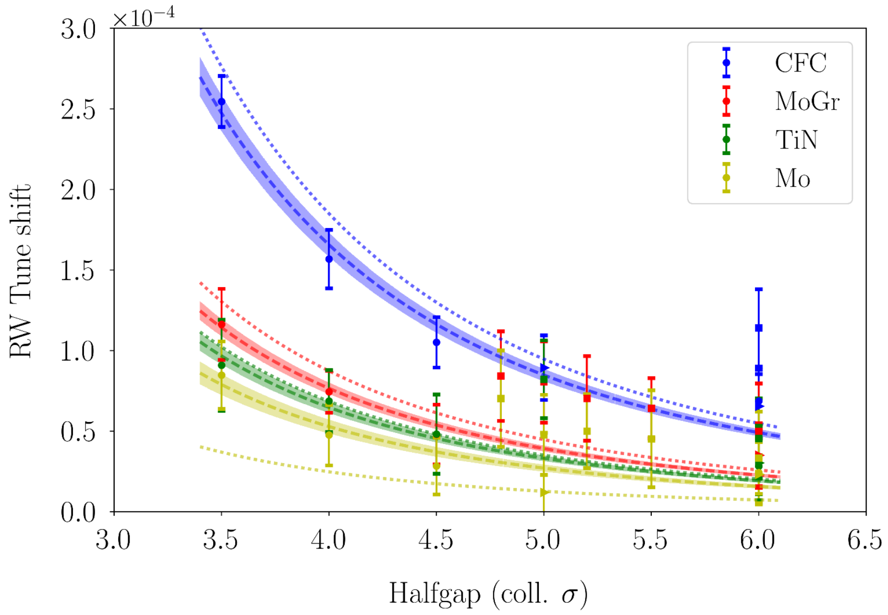


Figure 9: Measured TCSPM tune shift as a function of the collimator gap in units of σ. Cirles and squares with errorbars represent the data points of 2017 and 2018 respectively, dashed lines the fit to the measured data of 2017, dotted lines the expected behaviour for the nominal material resistivities.

confirm the hypothesis that the tertiary collimators have negligible contributions with respect to the IR7 collimators.

Second, the measurement performed on the secondary collimators showed a discrepancy of up to a factor of 2 larger tune shifts compared to impedance model predictions. During this MD activity beam parameters and in particular intensity losses were closely monitored, removing some possible sources for discrepancies. Effects like collimator jaw material ageing or jaws misalignment with respect to the beam are being investigated. Nevertheless, the large measured tune shifts of secondary collimators confirms the need to reduce the secondary collimators impedance as planned by the LHC collimation upgrade. Measurements done on the TCSPM collimator showed an increase of the tune shift of a factor of about 2, which could be related to collimator misalignment and/or jaw resistivity degradation due to radiation and will be subject of dedicated MDs during the LHC Run 3.

Acknowledgements

We would like to thank the OP crew, and in particular M. Albert, G. Crockford, B. Salvachua and S. Uznanski for their assistance during the MD activity.

References

[1] N. Mounet *et al.*, “Collimator Impedance Measurements in the LHC”, in *Proc. IPAC’13*, Shanghai, China, May 2013, paper TUPWA047, pp. 1817–1819.

[2] G. Apollinari, I. Bejar Alonso, O. Brüning, M. Lamont, L. Rossi (eds.), “High Luminosity Large Hadron Collider (HL-LHC) Technical Design Report V.01”, CERN, Geneva, Switzerland, EDMS n. 1723851 v.0.71, `https://edms.cern.ch/ui/file/1723851/0.71/HL_TDR_V07.0.2016.10.05.Version15.2h.pdf`

[3] A. Mereghetti *et al.*, “β^*-Reach – IR7 Collimation Hierarchy Limit and Impedance”, CERN LHC MD notes, January 2016, *CERN-ACC-NOTE-2016-0007*, `http://cds.cern.ch/record/2120132`.

[4] A. Mereghetti *et al.*, “MD1447 – β^*-Reach: IR7 Collimation Hierarchy Limit and Impedance”, CERN LHC MD notes, April 2020, *CERN-ACC-NOTE-2020-0021*, `http://cds.cern.ch/record/2715361?ln=en`.

[5] A. Mereghetti *et al.*, “MD1446 – Impedance Contribution of Primary Collimators”, CERN LHC MD notes, April 2020, *CERN-ACC-NOTE-2020-0020*, `http://cds.cern.ch/record/2715360?ln=en`.

[6] A. Mereghetti *et al.*, “MD1875 – Impedance Contribution of Secondary Collimators” , CERN LHC MD notes, April 2020, *CERN-ACC-NOTE-2020-0022* `http://cds.cern.ch/record/2715362?ln=en`.

[7] S. Redaelli *et al.*, “Staged implementation of low-impedance collimation in IR7: plans for LS2”, CERN ATS Notes, CERN-ACC-NOTE-2019-0001, January 2019, `http://cds.cern.ch/record/2654779`.

[8] R. Bruce, S. Redaelli, “Installation of a low-impedance secondary collimator (TCSPM) in IR7”, LHC Engineering Change Request, LHC-TC-EC-0006, November 2016, `edms.cern.ch/document/1705738`.

[9] A. Mereghetti *et al.*, “MD2193 – Impedance measurements of TCPSM collimator”, report in preparation.

[10] D. Valuch, “Excitation by ADT and Active Bunch by Bunch Tune Measurements”, presentation at the 129th SPS and LHC Machine Protection Panel Meeting, 10^{th} June 2016, CERN, Geneva, Switzerland.

[11] M. Soderen, D. Valuch, “ADT ObsBox Data Acquisition”, presentation at the LHC Beam Operation Committee, 13th June 2017, CERN, Geneva, Switzerland, `https://indico.cern.ch/event/645898`.

[12] A. Mereghetti *et al.*, “MD2191 – β^*-Reach: IR7 Collimation Hierarchy Limit and Impedance”, report in preparation.

[13] D. Amorim, “Tune shifts: measurements and predictions”, presentation at the 91st Collimation Upgrade Specification Meeting (ColUSM), 11th August 2017, CERN, Geneva, Switzerland, `https://indico.cern.ch/event/657903`.

[14] LHC OP elogbook, morning shift of 27th October 2018, `https://op-webtools.web.cern.ch/elogbook/index.php?shiftID=1104539&lgbk[]=60`

[15] LHC OP elogbook, afternoon shift of 27th October 2018, `https://op-webtools.web.cern.ch/elogbook/index.php?shiftID=1104550&lgbk[]=60`

[16] `pyjapc` repository, `https://gitlab.cern.ch/scripting-tools/pyjapc`

[17] L. Malina et al., “Performance Optimisation of Turn-by-Turn Beam Position Monitor Data Harmonic Analysis”, in *Proc. IPAC’18*, Vancouver, Canada, Apr.-May 2018, pp. 3064–3067.

[18] ImpedanceWake2D repository, `https://gitlab.cern.ch/IRIS/IW2D`.

[19] S. A. Antipov et al., "Tune shift difference found on TCSPM collimator", 35^{th} IWG meeting, CERN, Geneva, Switzerland, `https://indico.cern.ch/event/844161`