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MD2193 – Impedance Measurements of the TCSPM Prototype Collimator

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Summary

In view of the HL–LHC project, it is planned to exchange 9 out 11 of the LHC secondary collimators in IR7, made of graphite, with low–impedance ones. In order to optimise the new design, a prototype of collimator with a selection of low–impedance materials coated on the surface of the jaw was installed in the LHC during the 2016 Extended Year End Technical Stop, to be able to verify with beam the beneficial effects on impedance. This report summarises the measurements taken with the prototype collimator during MD2193, carried out in MD block 1 of 2017, on the night between 30$^{\text{th}}$ June and 1$^{\text{st}}$ July. An additional set of measurements was collected in parallel to MD2191, during MD block 3 of 2017, on the night between 17$^{\text{th}}$ and 18$^{\text{th}}$ September; in that occasion, an HL–LHC type of nominal bunch was used. As done in past activities of the same type, the impedance was estimated by measuring the tune shift induced on the beam by varying the collimator gap; the tune was reconstructed from the damped oscillations of the beam when coherently kicked with the ADT in AC–dipole mode, in order to have a strong tune signal. Measurements fit very well with expectations; however, Molybdenum remains the most promising material among the coated ones, even if a resistivity larger than the expected one was measured during the MD.

1 Introduction

The collimation system of the Large Hadron Collider (LHC) is responsible for a sizeable fraction of the LHC impedance budget [1]. The largest fraction is taken by the secondary collimators (TCSG) installed in the LHC Insertion Region (IR) dedicated to betatron cleaning, i.e. IR7; another family of collimators responsible for a relevant fraction of the impedance budget is that of the primary collimators (TCP) in the same IR.

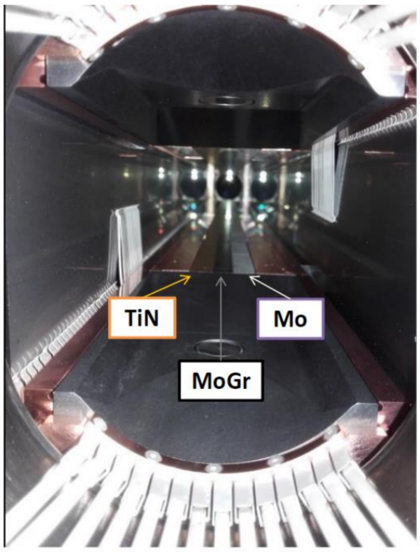

Figure 1: Inside of the TCSPM prototype. The materials of the three stripes are highlighted.

The High Luminosity LHC Project (HL–LHC) [2] foresees the deployment of beams brighter than those presently available, worsening the impact of collimators on impedance [3]. Therefore, as part of the upgrade of the LHC collimation system for HL–LHC, it is planned to exchange 9 out of 11 TCSGs with low–impedance collimators (TCSPM); their design [4] foresees a jaw in Molybdenum–Graphite (MoGr), with an additional coating layer. The new design is the result of an intense R&D program [5, 6, 7, 8] aimed at identifying jaw materials with a low impedance capable of standing the higher damage potential of HL–LHC beams [9], to replace the existing primary and secondary collimator families.

In order to finalise the choice of coating layer and validate the design of the new collimators, a prototype of TCSPM was installed during the 2016 Extended Year End Technical Stop (EYETS2016) of LHC [10]. The prototype is equipped with three stripes (see Fig. 1), that can be exposed to the beam, in order to measure their impact on impedance, e.g. by means of tune shift measurements. The exposure of a given stripe to the beam is achieved by means of the so–called "fifth axis" functionality, by which the whole collimator assembly, and hence the jaws, is moved transversely to the collimation plane. The three materials are MoGr (i.e. the native jaw material), TiN and Mo coatings on MoGr. The prototype is installed in the slot D4R7 on B2, on the vertical plane. This slot was chosen since it already hosts the TCSG.D4R7.B2 collimator, characterised by the smallest beam size σ among the secondary collimators; therefore, for the same normalised settings, the collimators at this slot minimise their physical gap in mm, maximising the effect on impedance, and hence pushing the sensitivity of the measurements.

During Run 2, a significant effort has been put in measuring the impedance contribution of collimators. For instance, MD314 [11] in 2015 and MD1447 [12] in 2016 were aimed at evaluating the impact on impedance from all the IR7 TCSG collimators at 6.5 TeV, whereas MD1446 [13] and MD1875 [14] were aimed at measuring at 6.5 TeV the impact on impedance from single collimators, in particular TCPs and TCSGs, respectively. These activities are important as they give the essential possibility to benchmark simulation models and numerical results against precise measurements with beam; moreover, they were the occasion to test with beam the feasibility of configurations actually deployed for LHC operation in recent years; finally, they allowed to push the accuracy of tune shift measurements to unprecedented levels, paving the way to the measurements presented here where low–impedance materials have to be characterised with beam.

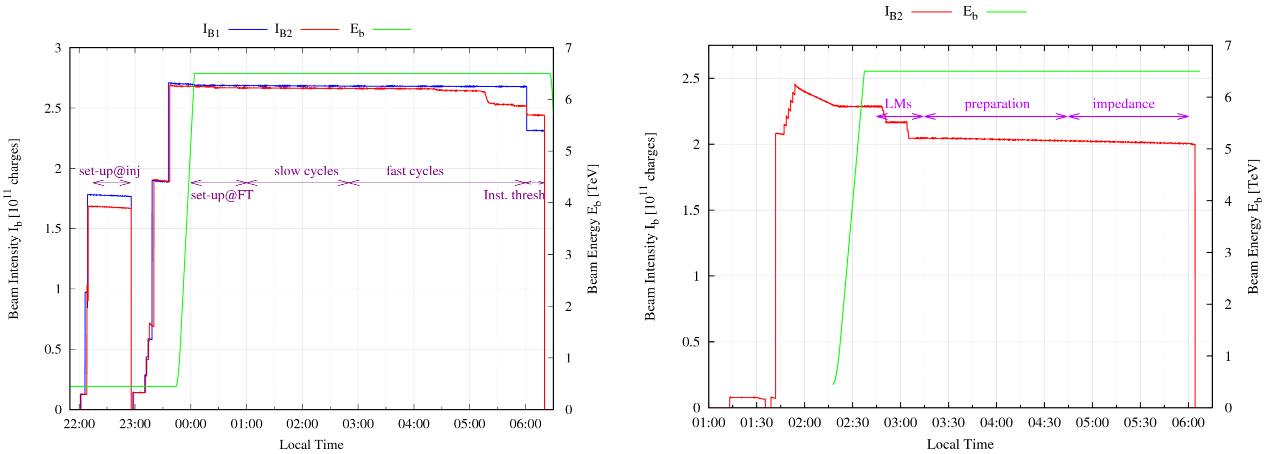

Figure 2: Intensity of B1 (blue curve) and B2 (red curve) as read by the fast beam current transformer (BCTFR), and beam energy (green curve) during the presented MD activity. The time periods of the main activities carried out are highlighted. MD2193 (left plot): set–up at injection and flat top, tune shift measurements where collimators were cycled slowly and quickly, and instability threshold measurements. Measurements in parallel to MD2191 on B2 (right plot): loss maps (not reported here, see Ref. [15]), set–up at flat top, and tune shift measurements with quickly cycled collimator gaps.

The aim of the MD activities presented in this report is to measure with beam the impact on impedance of the three materials available on the TCSPM prototype. The adjacent TCSG.D4R7.B2 was measured as well, for direct comparison. The measurements reported here were obtained mainly during MD2193 with nominal bunches; additional measurements were taken on B2 in parallel to MD2191 [15], with an HL–LHC type of bunch.

2 Procedure and Beam Conditions

The impact on impedance was quantified by measuring the tune shift induced on the beam when varying the collimator gap. The expected tune shift is smaller than the resolution of BBQ measurements. Hence, the same procedure as the one tested in past MD activities of the same type was deployed [11, 12, 13, 14], i.e. the beam was coherently kicked with the transverse damper (ADT) used in AC–dipole mode [16] and the tune was reconstructed from the damped oscillations observed with the ADT ObsBox [17].

2.1 MD2193

The MD activity was carried out on the night between 30^{th} June and 1^{st} July 2017 [18, 19], at 6.5 TeV. The optics at flat top was used, at the end of the "combined ramp and squeeze" beam process i.e. with no tune change and without squeezing beams down to a β^* of 40 cm or 30 cm but remaining at 3 m, or collapsing the bumps for parallel separation at the interaction points (IPs), since the settings of the IR7 collimators do not change throughout these machine configurations.

The left frame of Fig. 2 shows the time evolution of beam energy and current, with labels indicating the main activities during the MD. Prior to the actual measurement campaign, the ADT kicking was set up at injection; at the same time, the fifth axis functionality of the TCSPM was verified. Once at flat top, the ADT settings for kicking were fine tuned, in order to have kicks strong enough but with minimal beam losses and tail scraping; at the same time, chromaticity / octupoles / damper were optimized to improve the coherent oscillation of the kicked beam for best measuring the tune shifts, and the measured collimators were aligned to the beam, in order to ensure optimum centering. The TCSG.D4R7.B2 was aligned to the beam using the associated beam loss monitors (BLMs) by means of the BLM–based alignment; on the contrary, being equipped with beam position monitors (BPMs), the TCSPM.D4R7.B2 was aligned to the beam by means of the BPM–based alignment. It should be noted that the alignment was performed with the TCSPM gap at 40 mm and the 5$^{\mathrm{th}}$ axis at 10 mm; therefore, centring was not optimal, i.e. the beam centre was off the collimator centre by $\sim$150 μm according to BPM readouts [20], corresponding to 0.75 σ with a normalised emittance of 3.5 μm; such an offset is at the limit of typical alignment accuracy [15]. An offline analysis [20] of the BPM readouts during measurements indicates a mis–tilting angle between beam and jaws of about 100 μrad when the fifth axis is moved back to 0 mm (therefore BPM buttons nominally at the beam).

A first set of measurements was carried out slowly cycling the gap of the measured collimators, allowing several kicks of the beam in sequence for the same gap; these measurements were affected by extremely large tune drifts, randomly enlarging / reducing the measured tune shifts and hence completely spoiling the measurements. It was then decided to cycle quickly the gap of the collimator being measured, allowing just two or three consecutive kicks of the beam for the same gap; in this way, all the measured tunes are affected by the same drift, which can be fitted and removed with appropriate analyses (Fig. 3). This second method allowed to collect plenty of data. Finally, the MD activity was closed by an instability threshold measurement.

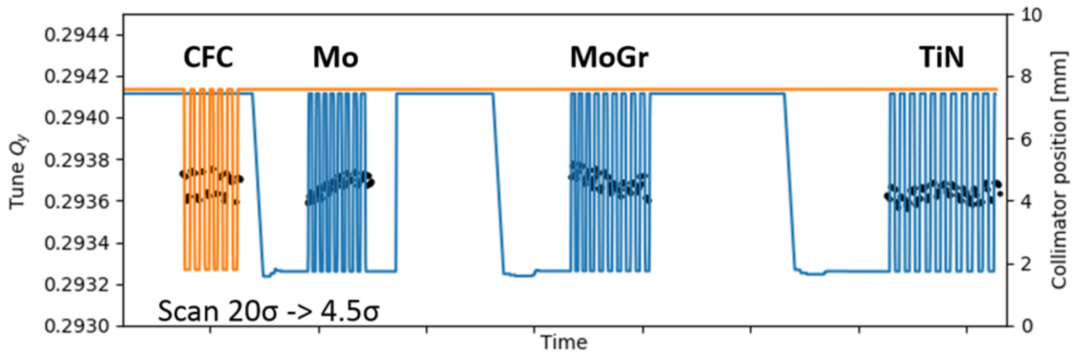

Figure 3: The modified measurement procedure. The raw tune data shows a clear reduction of the tune shift with the new coatings with respect to the CFC. A significant tune drift during the measurement can also be seen. The orange line depicts the position of the CFC TCSG collimator, whereas the blue line depicts the 3–stripe collimator TCSPM. The dots show the individual tune measurements.

Measurements were carried out with two nominal bunches, decreased ADT gain, chromaticity lowered down to 5 units in both beams and planes (from the operational value of 15), and the octupole current set to 270 A. The injection scheme used for the activity was the `Single_10b_3_0_0_pilots_7nc_1c`. The two nominal bunches were in buckets 1 and 5241 on B1, and 141 and 5141 on B2. They had different intensities, i.e. $\sim$0.8 and 1.2×10^{11} protons per bunch. No exact measurement of beam emittance was done; the normalized transverse emittance was estimated to be between 2 and 2.5 μm.

In order to reduce the risks of instabilities during the MD activity, and hence spoil the good characteristics of the bunches, all IR7 TCSGs were opened to 20 σ; this is also the largest collimator setting used when cycling collimator gaps. Gaps were cycled with 3.5, 4.0, 4.5, and 6 σ as minimum values. Priority was given to the last two values, to reduce the risk of instabilities and hence secure some useful data before approaching tighter minimum settings. When approaching the most challenging setting of 3.5 σ, a transverse instability was observed on the 1.2×10^{11} p bunch (as expected) and about 20% of its intensity was lost. After stabilizing the beam the study was continued.

The tune shift measurements were performed with each stripe of the TCSPM; in order to avoid scratching the coated surfaces (and hence perturbing the conductivity of the layers), whenever a minimum setting smaller than previous ones was measured, the beam was scraped with the TCP; for the same reason, kicking was performed while keeping the TCSPM in the shadow of the TCP, i.e. with the settings of the latter at least 0.2 σ smaller than those of the former. For comparison, the TCSG.D4R7.B2 was measured as well, and hence its gap cycled as done for the TCSPM.

2.2 Measurements Taken in Parallel to MD2191

These measurements were taken on the night between 17$^{\text{th}}$ and 18$^{\text{th}}$ September 2017 [21], at 6.5 TeV. The same optics as the one used in MD2193 was deployed (see Sec. 2.1).

The right frame of Fig. 2 shows the time evolution of beam energy and current, with labels indicating the main activities during the MD. Measurements were taken with B2 only, since the prototype of TCSPM is installed only on this beam; moreover, the original activities foreseen for MD2191 were carried out only on B1. Similarly to MD2193 (see Sec. 2.1), prior to the actual measurement campaign, some time was dedicated to setting up the ADT kicking, optimising chromaticity / octupoles / damper, verifying the fifth axis functionality of the TCSPM, and re–alignment to the beam of the TCSPM.D4R7.B2 collimator. It should be noted that the alignment was performed with the TCSPM gap at 10 mm and the fifth axis at 10 mm; therefore, centring was not optimal, i.e. the beam centre was off the collimator centre by 50 μm according to BPM readouts [20], corresponding to 0.25 σ with a normalised emittance of 3.5 μm; such an offset is comparable to the typical alignment accuracy [15]. An offline analysis [20] of the BPM readouts during measurements indicates a mis–tilting angle between beam and jaws of about 10 μrad when the fifth axis is moved back to 0 mm (therefore BPM buttons nominally at the beam). The TCSG.D4R7.B2 was not re–aligned. The set–up phase took longer than for MD2193, since activities had to be interleaved with those of MD2191 carried out in parallel on B1. Afterwards, the actual tune shift measurements were carried out. Profiting from the experience gained in MD2193 (see Sec. 2.1), the tune shifts were recorded while quickly cycling the collimator gaps.

Only a nominal bunch with characteristics very similar to those envisaged by the HL–LHC project was deployed; the bunch had $\sim 1.9\times10^{11}$ protons. Measurements were taken with halved ADT gain, chromaticity lowered down to 7 on both planes (from the operational value of 15), and the octupole current set to 270 A. The injection scheme used for the activity was the "30 bunches for MUFO spaced", as done in MD1447 [12]; the nominal bunch was injected in bucket 201.

As done in MD2193 (see Sec. 2.1), all IR7 TCSGs on B2 were opened to 20 σ; on the contrary, there was time to cycle gaps only with 5 and 6 σ as minimum values. Particular care was taken with the TCSPM to avoid scratching the coated surfaces, as done in MD2193.

3 Results of Impedance Measurements

When determining the tune shift of individual collimators, one of the challenges is the drift of the tune over the time of the measurement. The magnitude of the drift of 10^{-4} can be significantly greater than that of the single collimator shift of $\sim 10^{-5}$, making it hard to quantify or even detect the latter. Thus, in order to quantify the tune shift, one first needs to filter out the drift. Fortunately, it is possible to do so, provided that the measurement dataset is large enough.

3.1 Tune jitter

The tune jitter was identified and corrected for by, first, separating the data into subsets based on the collimator position; each subset should have its own tune, which should remain constant in the absence of the jitter. Then, the average tune for each subset was found and subtracted, such that the remaining signal corresponds to the tune jitter. Finally, the subsets were merged together to find the temporal dependence of the tune drift. During the MD we observed a drift of the tune with a full swing of up to 10^{-4} and rms variation of more than 2.5×10^{-5} (Fig. 4). The observed slow tune jitter with a $\sim$100 s period might become an issue for HL–LHC. It may arise from the temperature fluctuations or the noise in the orbit feedback system. A thorough investigation is required to establish a correlation with the source of the jitter.

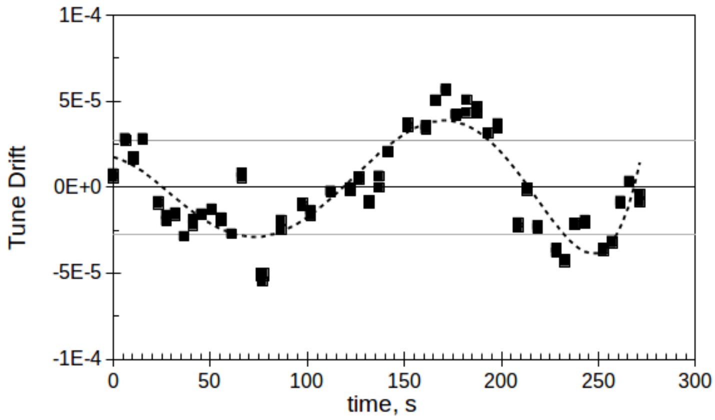

Figure 4: A slow tune jitter with a $\sim$100 s period is observed during the ADT excitation tune measurements. The thin gray lines show the rms spread of about $\pm 2 \times 10^{-5}$.

For the purpose of this study, we restricted ourselves to solely identifying and accounting for the tune jitter. After the slow drift has been corrected one can clearly distinguish the tunes for open and closed jaws for the studied coatings and collimator retractions (see Fig. 5). With the datasets of $\sim$100 measurements per coating and collimator gap one can achieve the level of 10^{-5} in the tune uncertainty. The results are summarized in Table 1. Note that the data for the 3.5 σ retraction were collected after an accidental loss of $\sim$20% of the beam intensity (see Sec. 2.1). Results have been scaled up to the nominal intensity during the post–processing.

3.2 Measurements with nominal–ish LHC bunches

For some collimator gaps the tune shifts of different low–impedance coatings are similar within the error bars of the measurement, thanks to their low impedance (Fig. 6). In order to quantify the difference between them one has to fit the data for several collimator gaps. That allows the separation of the resistive wall and geometric impedance. Although the latter is typically small (of the order of or less than 10–20 %), its effect might be non–negligible for the low–resistivity collimator materials.

Since the resistive wall contribution to the impedance is inversely proportional to the cube of the collimator gap (see, for example, [22]), its contribution to the tune shift can be represented

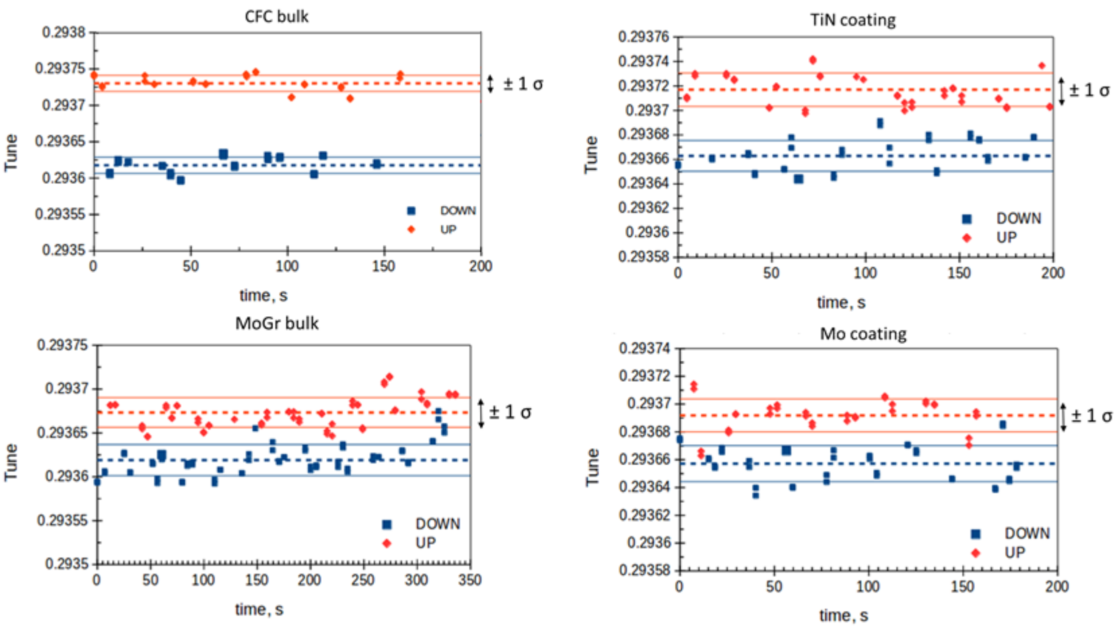

Figure 5: The difference in the measured tunes is clearly seen for all 4 coatings. Individual tunes can be measured with a statistical uncertainty of $\pm 10^{-5}$. The shown data are those collected with 4.5 σ as minimum value of the cycled gap.

as

$$\Delta Q_{rw} \propto A_{rw}/n_\sigma^3, \tag{1}$$

where n_σ is the half gap in collimation units σ, and A_{rw} is the coefficient, proportional to the square root of the resistivity of the material: $A_{rw} \propto \sqrt{\rho}$. The contribution of the geometric impedance to the tune shift can be well described as [23]

$$\Delta Q_{geom} \propto A_{geom}/n_\sigma^2, \tag{2}$$

where A_{geom} is a constant. Fitting the data allows distinguishing between the Mo and TiN coatings and MoGr bulk (Fig. 6). It is clear that Mo coating offers the largest reduction of the impedance.

The experimental results were compared with the theoretical predictions of the current LHC impedance model of the LHC, computed using the IW2D code [24]. The TCSPM collimator is simulated as a TCSG with a different jaw material. The model incorporated both resistive wall and geometric impedance. It is assumed that the geometric impedance is the same for all three stripes and only their resistivity changes and is the same for TCSG and TCSPM. According to the data, the geometric contribution is non–negligible and is responsible for nearly 10 % of the total TCSG impedance at 6σ, consistent with the impedance model predictions. After the geometric component is accounted for, the IW2D model agrees with the fitted experimental data for CFC, MoGr bulk, and TiN with a discrepancy from 10 to 20 % (Fig. 6). Table 2 summarizes the results of the TCSPM test in terms of the measured resistivity.

The Mo stripe data significantly differs from the model predictions. The measured tune shift is roughly a factor two greater than the expected one. A probable cause of the discrepancy could be the inhomogeneity of the Mo surface, discovered during the SEM imaging of coated surface samples [25]. Qualitatively, roughness of the surface increases the effective DC resistivity and thus the resistive wall tune shift [8], which is consistent with the measurements. A factor of ~ 2 observed in the measured tune shift would mean a factor of ~ 4 higher DC resistivity of the

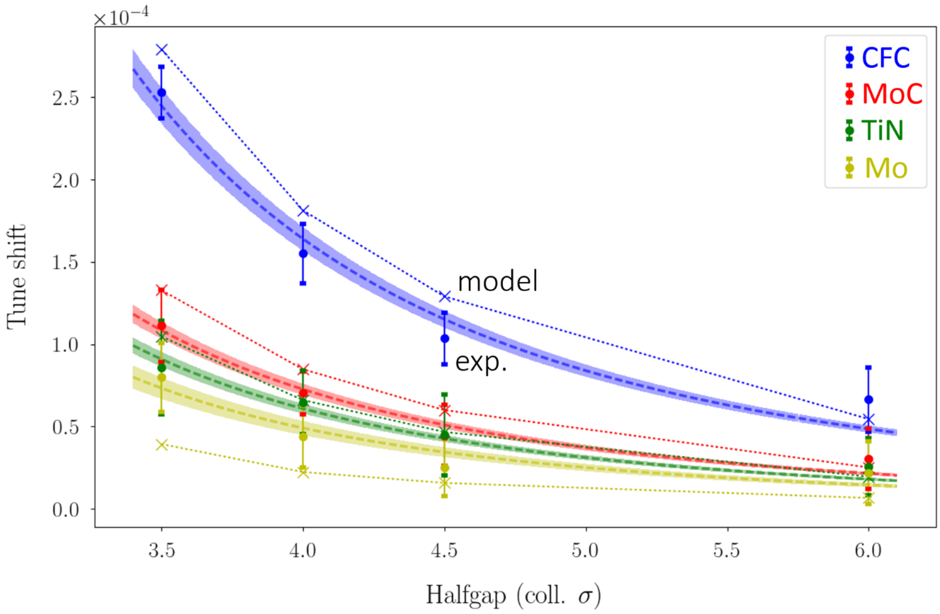

Figure 6: The usage of MoGr (red dots and curves, labelled in the figure as "MoC") reduces the resistive wall tune shift compared to the uncoated CFC (blue dots and curves); each type of coating: TiN (green) and Mo (yellow) further improves the conductivity and can be clearly differentiated. For all the collimator materials the measurement results (dashed curves) are within 10–20% of the model predictions (dotted lines), but for Mo.

Table 1: Measured tune shifts ΔQ [10^{-5}] for various gaps and collimator materials.

Material	3.5 σ	4.0 σ	4.5 σ	6.0 σ
CFC	26.8 ± 1.6	16.7 ± 1.8	11.3 ± 1.6	7.2 ± 1.9
MoGr	12.7 ± 2.2	8.2 ± 1.3	5.4 ± 1.8	3.6 ± 1.8
TiN	10.2 ± 2.8	7.7 ± 1.9	5.4 ± 2.5	3.1 ± 1.7
Mo	9.5 ± 2.0	5.6 ± 1.9	3.5 ± 1.8	2.7 ± 1.9

Table 2: The resistivities of different coatings: measured values and expectations from the IW2D [24] impedance model in [n$\Omega\times$m]; the ratio between the two is also given, for the reader's convenience.

Material	Measured	Expected	Ratio
CFC	4030 ± 380	5000	0.806 ± 0.076
MoGr	760 ± 60	1000	0.76 ± 0.06
TiN	340 ± 40	400	0.85 ± 0.1
Mo	250 ± 50	50	5 ± 1

coating with respect to the bulk Mo. After the MD, a detailed study was launched examining different techniques of Mo film deposition and obtained a sound estimate of the DC resistivity of thin Mo coatings [30].

It should be noted that a dedicated sensitivity study about misalignment or mis–tilting was not carried out. In the scope of the presented results, the coating quality is more relevant, since a large discrepancy is seen only on one stripe, whereas mis–tilting and misalignments should affect all stripes at the same time, though differently, since the two affect the jaws as a whole. In addition, as it will be seen in the next section, data taking with an HL–LHC–like intensity bunch show the same discrepancy between impedance measurements and predictions even though the alignment accuracy (reconstructed a–posteriori, see Secs. 2.1 and 2.2) was better.

3.3 Measurements with an HL–LHC–like intensity bunch

The primary goal of the second measurement was to verify the reduction of resistive wall tune shift, observed in the first measurement, in the conditions close to those foreseen by the HL–LHC project. To do so, a high intensity bunch of 1.9×10^{11} protons was used. The collimator gaps were cycled with 5 and 6 σ as minimum gaps (for a 3.5 μm reference emittance). It should be noted that these settings are tighter than those envisaged for the future HL–LHC operation [26].

As expected, the largest improvement of the resistive wall tune shift was observed for the Mo coating, i.e. 3 times lower than that of the CFC with the 6σ retraction; MoGr bulk and TiN coating showed a similar improvement by a factor 2 compared to CFC (Fig. 7). For most of the studied scenarios the measured and the simulated resistive wall tune shifts were in good agreement, except for the Mo stripe. The Mo showed a larger shift than expected, consistent with the results of MD2193. Little data was obtained at 5 σ retraction due to the time constraints of the MD. The experimental data was in good agreement with the model for CFC and a visible improvement was observed for the Mo stripe.

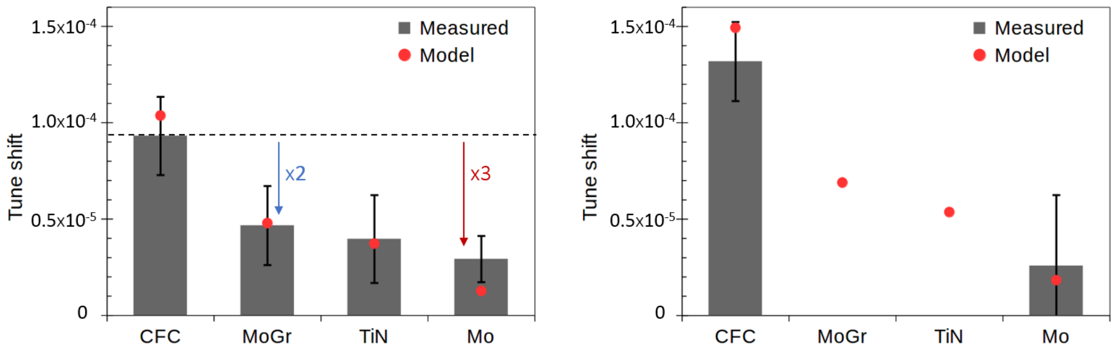

Figure 7: Resistive wall tune shift plotted for different coatings, $E = 6.5$ TeV, bunch intensity 1.9×10^{11} p for different values of minimum cycled gap: 6σ (left frame) and 5σ (right frame). The error bars reflect the measurement reproducibility between different kicks. In particular, the larger error bar of the Mo measurement at 5σ is due to a smaller data set.

At last, we performed a test in order to rule out the presence of the higher resistivity stripes adjacent to Mo as the cause of the discrepancy in its measured tune shift. If within the Mo stripe a variation of the tune shift with the fifth axis position were observed, that would indicate a possible effect of the adjacent materials. The large error bars of the measurement do not allow giving a definitive answer whether the presence of the higher resistivity MoGr stripe next to the Mo stripe affects the results (Fig. 8). Still, within 1/5 of the stripe width the measured shifts are essentially the same, suggesting that even if the effect exists, it should be relatively small. This finding is also consistent with the results of numerical simulations, predicting the width of the transition region between the stripes to be about or less than 2 mm, significantly smaller than the stripe width [27].

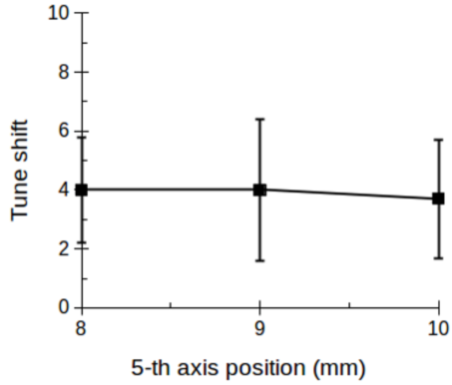

Figure 8: Total tune shift ($\times 10^{-5}$) for 6σ halfgap while scanning the fifth axis position from the center of the Mo stripe (at 10 mm) towards the MoGr stripe (at 0 mm); the edge between Mo and MoGr is at 5 mm.

4 Instability analysis

Two transverse instabilities have been observed in the horizontal plane of Beam 2 during the TCSPM impedance test in MD2193 (Beam 1 was left intact during the impedance measurements). Table 3 briefly lists their key conditions and features. For some observables, such as the beam emittance, no exact values are available and reasonable estimates were used in the analysis. Overall, the two observed instabilities agree, both qualitatively and quantitatively with the predictions of the LHC impedance model.

The first instability was observed during an alignment test of the TCSPM collimator when the chromaticity was lowered from 15 to 10 units. The 1.2×10^{11} p bunch became unstable in the horizontal plane. The observed radial mode 2 and azimuthal mode 0 (see Appendix A for more details) are typical for impedance–driven instabilities at the LHC flat–top in the presence of the ADT and with a chromaticity close to 15. From the impedance model predictions, an increase of the required octupole current is expected around $Q' = 10$, but octupole current was $\sim$30% above that threshold for a Gaussian bunch (Fig. 9). The instability can be explained if one assumes that the tails of the transverse distribution had been cut during the alignment procedure. Cutting of the tails, in turns, leads to a narrower octupole stability diagram [28] and higher threshold ("parabolic" line in Fig. 9).

The second instability was observed in the horizontal plane when the TCSG collimator was pushed closer than 4 σ. The instability was expected from the impedance model: according to a preliminary prediction [29], the octupole threshold would be exceeded below 4 σ, when the instability actually happened at a separation of 3.9 σ (Fig. 10). Considering the typical uncertainty on emittance measurements and profile distribution, the agreement between the predictions and the observations can be considered satisfactory.

Table 3: Key parameters of the instabilities observed during MD2193; "-" indicates missing data, "$\sim$" - estimated data for which no exact value is available. m is the azimuthal mode number, whereas l the radial one.

Time	Plane	N_b [10^{11}]	Q', h/v	ϵ_n, h/v [μm]	m	l	τ [s]	d [turns]	I_{oct} [A]	σ_z [cm]
00:23	B2H	1.2	10/10	$\sim$2.5/2.5	0	2	9.4	$\sim$100	376	8.1
04:25	B2H	0.8	12/7	$\sim$2.5/2.0	0	–	12.7	$\sim$100	276	7.6

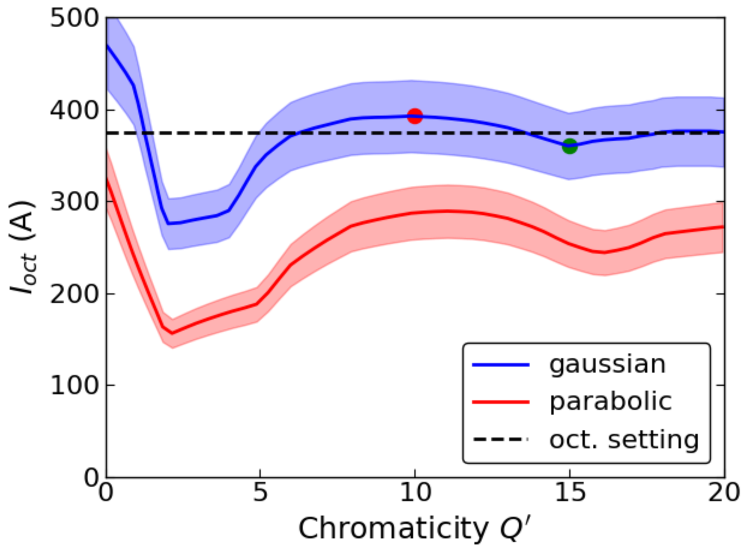

Figure 9: Simulation prediction of the octupole threshold for different transverse distributions. The beams go unstable as the chromaticity setting is reduced from 15 (blue circle) to 10 (red circle) and the octupole threshold is exceeded. A typical uncertainty of $\sim$ 10% has been considered from the emittance measurement.

5 Conclusions

Challenging measurements of the tune shift induced by changing the gap of the TCSG.D4R7.B2 and of the TCSPM.D4R7.B2 collimators were carried out; while for the former the impedance of only the original jaw material was measured, for the latter all the stripes were measured. Measurements were carried out coherently kicking the beams with the ADT in AC–dipole mode and reconstructing the induced tune shift from the damped oscillations; this method increases the reliability and sensitivity of the estimated tune shifts with respect to what can be achieved with the BBQ.

Measurements were carried out cycling the gap of the measured collimator between 20 σ and a minimum value, slowly tightened with care in order not to induce instabilities. Measured tune shifts fit quite well expectations from simulations, no matter the material or the chosen minimum gap; the only exception is the TCSPM when the Mo stripe is exposed to the beam, for which the measured tune shift is larger by a factor 2. This is, however, still the most promising coating material, and further investigations are required in order to understand the origin of the discrepancy. One possible explanation could be a non–optimal deposition of the Mo, inducing irregularities in the microscopic structure of the layer, with consequent increase of the impedance. Recent studies supported this hypothesis and correlated the deposition process to the final quality of the coating resistivity [30]

The measurement procedure used in the past to carry out similar activities was improved in this MD activity by cycling collimator gaps quickly instead of slowly; in this way, it was possible to limit the degradation of the measurements by the continuous, unavoidable and unpredictable tune shifts visible in the raw data.

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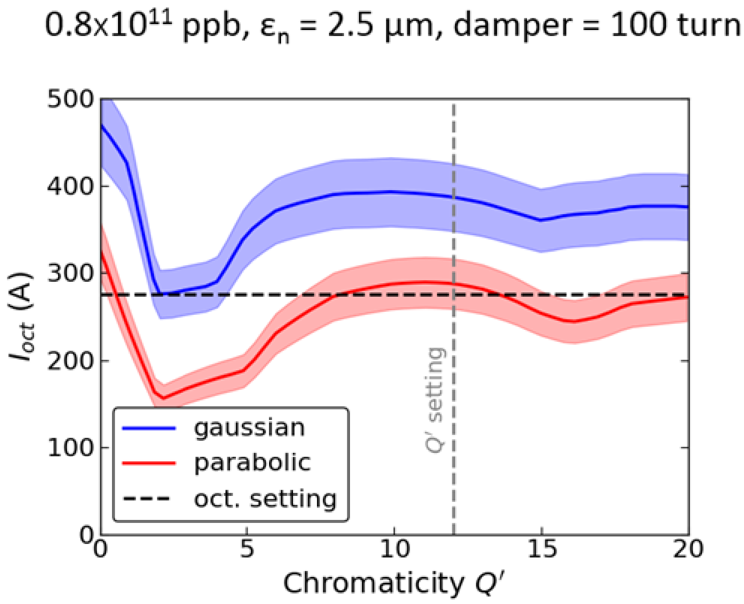

Figure 10: Simulated instability threshold agrees with the observations: the octupole threshold of 276 A is exceeded as the collimator gap decreases below 4 σ. A typical uncertainty of $\sim$ 10% has been considered from the emittance measurement.

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A Instability observations

This Appendix presents additional data on the instabilities observed during MD2193, quoted but not shown in the main body of the text for the sake of clarity.

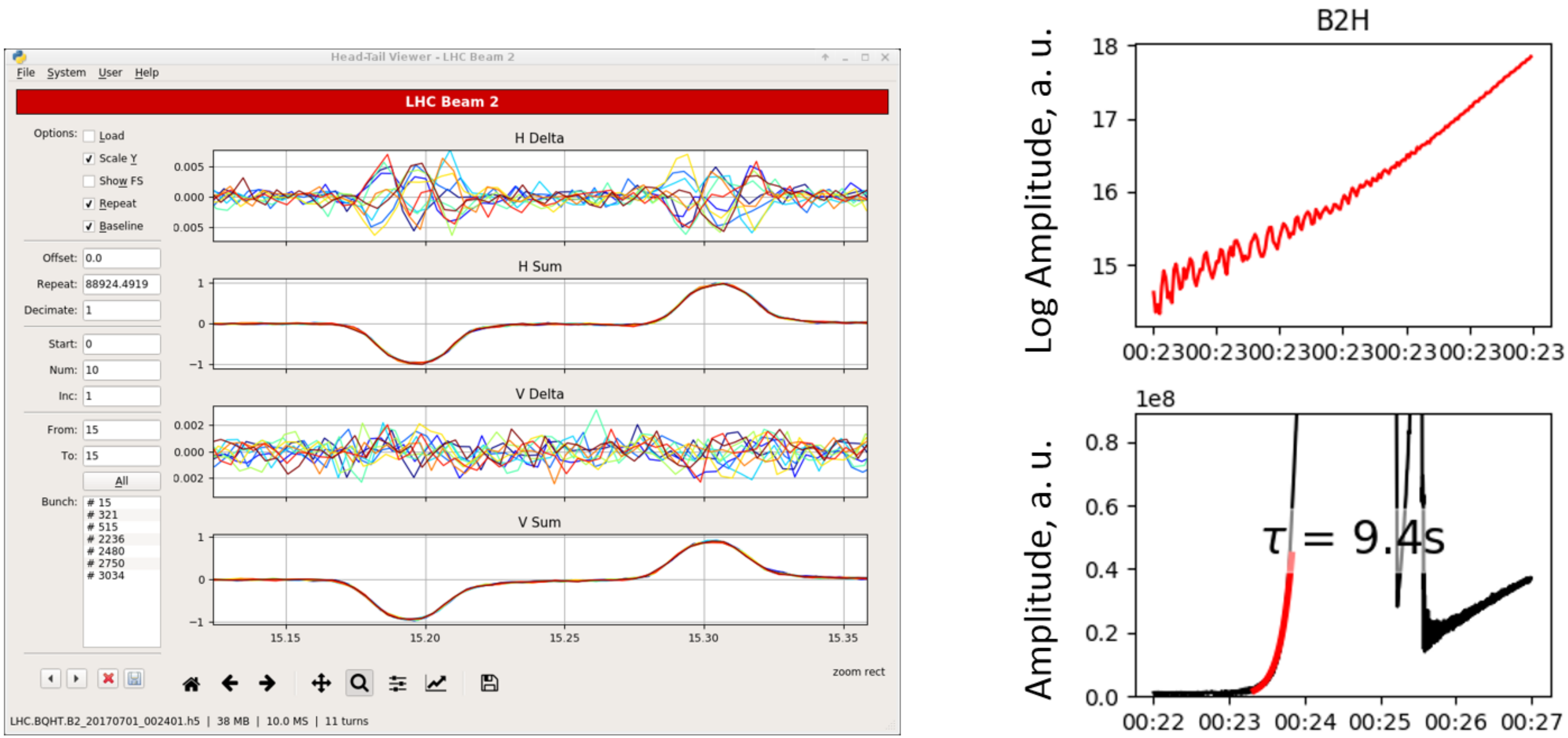

Figure A.1: Observation of the first instability in B2 (see Tab. 3). Head–tail monitor (left) shows a radial mode 2 in the horizontal plane, while the center of mass oscillations increase exponentially (right) with a rise time of 9.4 s.

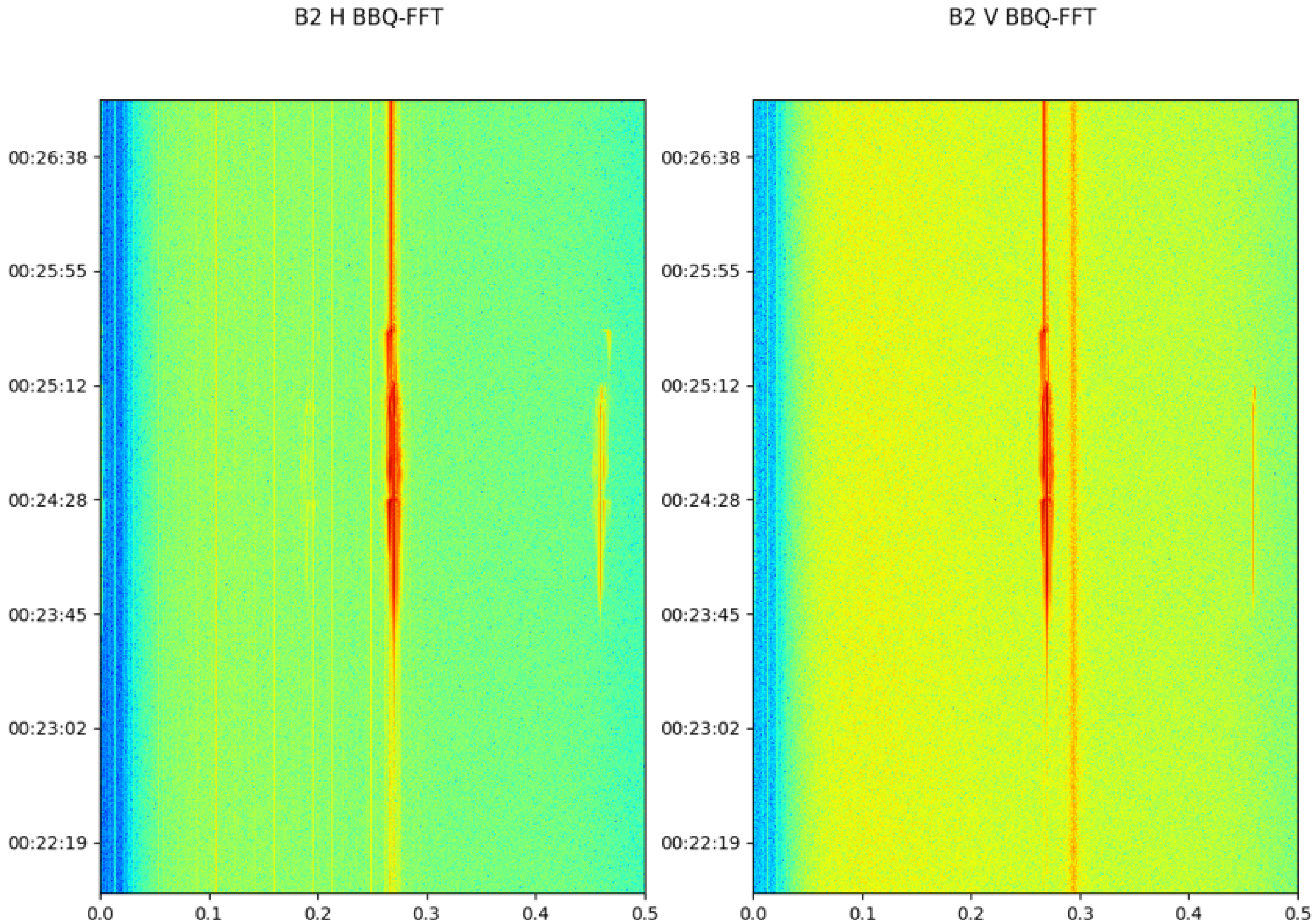

Figure A.2: Spectrogram images of the first instability in B2 (see Tab. 3): left – horizontal and right – vertical plane.

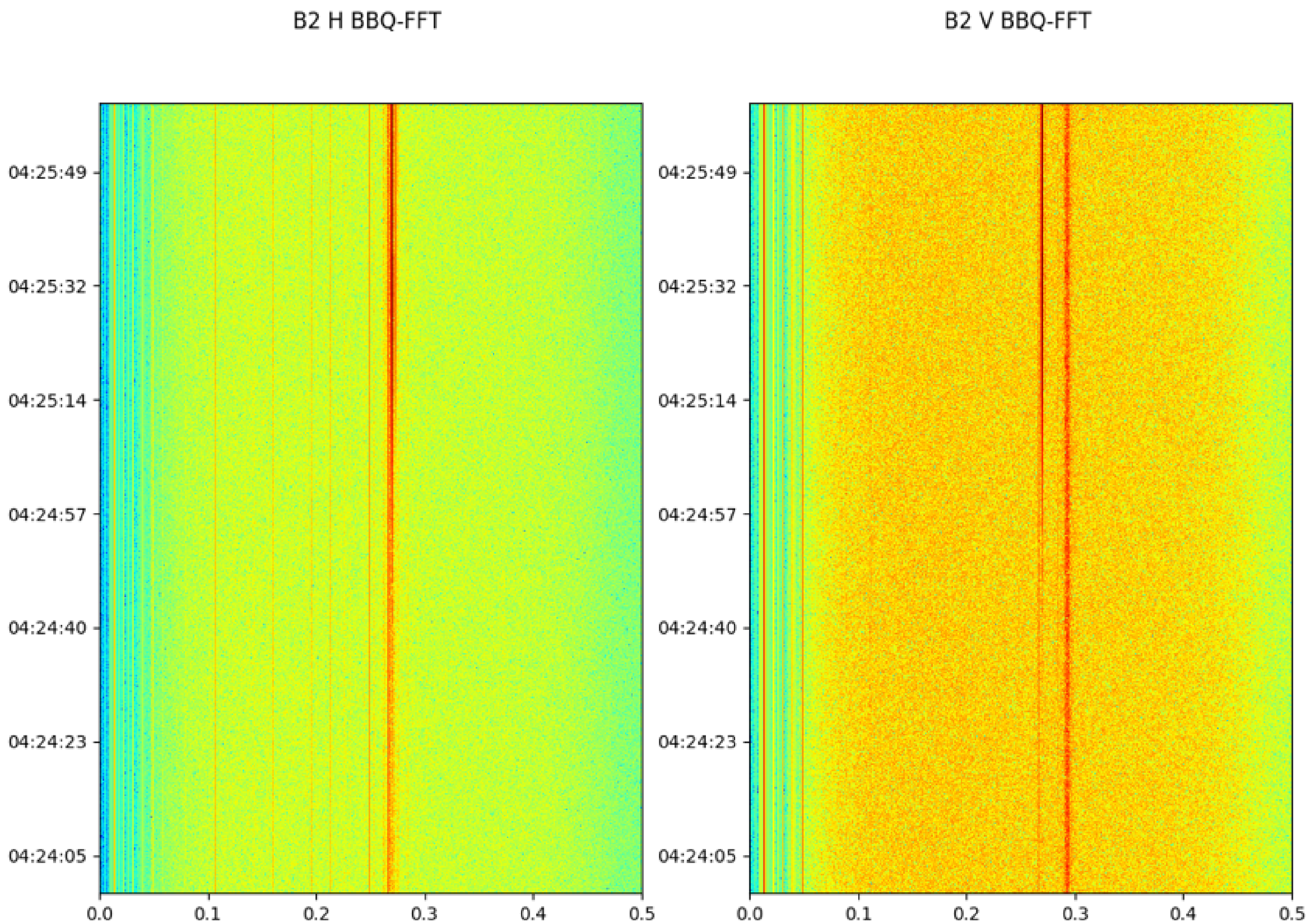

Figure A.3: Spectrogram images of the second instability in B2 (see Tab. 3): left – horizontal and right – vertical plane.