MEASUREMENT AND INTERPRETATION OF TRANSVERSE BEAM INSTABILITIES IN THE CERN LARGE HADRON COLLIDER (LHC) AND EXTRAPOLATIONS TO HL-LHC

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Abstract

Since the first transverse instability observed in 2010, many studies have been performed on both measurement and simulation sides and several lessons have been learned. In a machine like the LHC, not only all the mechanisms have to be understood separately, but the possible interplays between the different phenomena need to be analyzed in detail, including the beam-coupling impedance (with in particular all the necessary collimators to protect the machine but also new equipment such as crab cavities for HL-LHC), linear and nonlinear chromaticity, Landau octupoles (and other intrinsic nonlinearities), transverse damper, space charge, beam-beam (long-range and head-on), electron cloud, linear coupling strength, tune separation between the transverse planes, tune split between the two beams, transverse beam separation between the two beams, etc. This paper reviews all the transverse beam instabilities observed and simulated so far, the mitigation measures which have been put in place, the remaining questions and challenges and some recommendations for the future.

INTRODUCTION

The first transverse instability in the LHC was observed during the first ramp tried with a single bunch of ~ 10^{11} p/b (on both beams B1 and B2) on 15/05/2010, with neither Landau octupoles (dedicated magnets used to provide transverse Landau damping and whose maximum absolute current is 550 A) nor transverse damper [1]. A dedicated study was then performed on 17/05/10 at 3.5 TeV starting with a Landau octupole current of – 200 A (the minus sign refers to the focusing octupole family, which corresponds to a negative amplitude detuning) and reducing it in steps until the bunch became unstable between ~ – 20 A and – 10 A. Figure 1(left) shows the measurement of the instability rise-time (~ 10 s) in the time domain while Fig. 1(right) reveals the behaviour in the frequency domain, where the similar rise-time, from the (azimuthal) mode – 1, could also be deduced [1]). This instability has been found to be in good agreement with prediction from the impedance model (within a factor ~ 2 or less), requiring a modest amount of Landau octupole current. Further measurements were performed in 2010 and 2011 in multi-bunch (with trains of bunches), revealing also a relatively good agreement with the impedance model (within a factor ~ 2) [2].

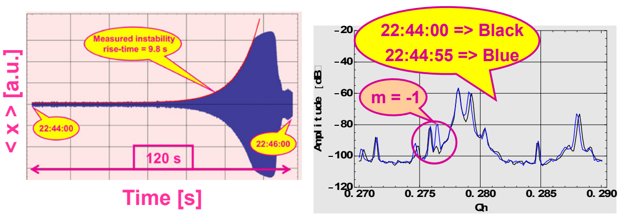

Figure 1: Dedicated single-bunch instability measurement at 3.5 TeV, two days after the first LHC transverse instability observed in 2010: (left) in the time domain and (right) in the frequency domain.

Things started to become more involved when we tried to push the performance of the LHC in 2011, and in particular in 2012. Several instabilities were observed at different stages of the LHC cycle, which perturbed the intensity ramp-up. All these instabilities could be cured by increasing the current of the Landau octupoles, the chromaticities and/or the gain of the transverse damper, except one transverse instability which remained at the end of the betatron squeeze [3,4]. Since then, transverse instabilities have been a worry for the future operation of the LHC and for HL-LHC [5].

The instability observations, the actions taken and the lessons learned are reviewed in Section 1 for the Run 1 (2010 to 2012), in Sections 2 and 3 for 2015 and 2016 respectively, while the future is discussed in Section 4.

RUN 1 (2010-2012)

The operation during Run 1 was performed with the 50 ns bunch spacing beam and with a lower energy (3.5 TeV first and then 4 TeV in 2012), and three types (in fact two after careful analysis) of instabilities perturbed the intensity ramp-up, which are discussed below.

In Collision: "snowflakes"

These instabilities happened always in the horizontal plane only and for both beams (see an example in Fig. 2). It concerned initially only the IP8 private bunches, i.e. the bunches colliding only at the Interaction Point 8. This was rapidly identified and these instabilities disappeared once the filling scheme was modified. The interpretation of this mechanism is that it happens on selected bunches with insufficient tune spread (and thus Landau damping) due to no head-on collisions, or transverse offsets [3,4].

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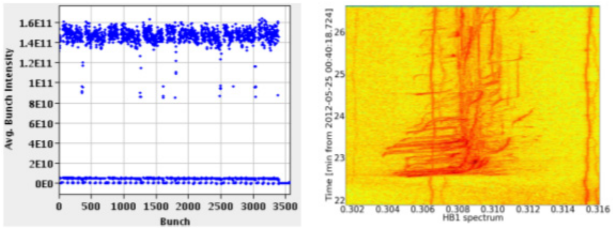

Figure 2: Example of “snowflakes” instability: (left) bunch intensity vs. number of the bunch (25 ns slot) and (right) horizontal frequency spectrum vs. time [3].

Putting the Beams Into Collision

A second type of instabilities happened at the end of the collision process, with the separation bumps collapsed, when ending with residual separations of ~ 2.1 σ in IP1 and ~ 1.2 σ in IP5 (values estimated from luminosities at the moment of the dump). These instabilities happened also in the horizontal plane. However, after careful analysis, it appeared that this type of instabilities happened only once or twice during the intensity ramp-up and it was never observed later in operational conditions.

During or at the End of the Squeeze Process

A third type of instabilities happened during or at the end of the squeeze, called EOSI (End Of Squeeze Instability), also in the horizontal plane. A characteristic picture is shown in Fig. 3(left), where 3 lines spaced by the (small-amplitude) synchrotron tune can be observed.

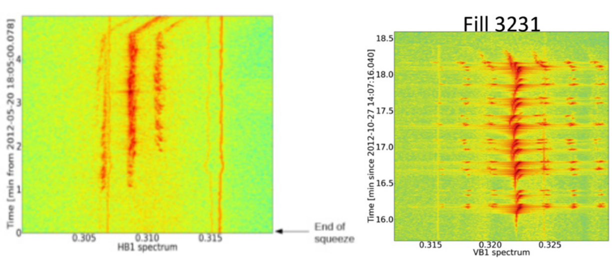

Figure 3: (Left) example of instability observed at the end of the squeeze: horizontal frequency spectrum vs. time after the end of the squeeze; (right) similar as in the left but after the “Middle of the Year Changes” [3,4].

Actions Taken

Based on the past work [6,7,1,2], the initial recommendations at the beginning of Run 1 were to try and keep the chromaticities as low as possible (~ 1-2) and to try and reduce the transverse damper gain as much as we could (to minimize the possible noise introduced and the associated transverse emittance growth). However, the issues discussed above rapidly appeared during spring and several actions were taken to continue and push the performance: (i) to avoid the beam dumps triggered during the collision process, it was proposed to change the sign of the Landau octupoles such that the tune spreads from beam-beam and octupoles do not fight against each other [8]; (ii) new values for the gain of the transverse damper, chromaticities and Landau octupole current were then suggested after a new analytical approach [9,10]. Indeed, it was found that if the transverse damper is not fully bunch-by-bunch, and if the chromaticity is not very well controlled (as it was the case during Run 1) then it is preferable to operate at relatively large chromaticity (~ 10-15) where a plateau is reached for the required stabilising octupole current. The first and second types of instabilities disappeared with the change of the Landau octupole polarity on August 7th (fill #2926) and the following increase of both the chromaticities and the gain of the transverse damper (which was then also used fully bunch-by-bunch during the squeeze): these changes are referred to as the “Middle of the Year Changes”. Unfortunately three parameters were modified almost at the same time and it was not possible to identify the main beneficial effect(s). The third type of instabilities could not be cured [3,4] (see Fig. 3(right)).

Lessons Learned

After detailed analysis, it seems that the main reason for which the situation improved after the “Middle of the Year Changes” was the increase of the chromaticity, which was not well controlled during Run 1, and running at high chromaticity prevented to reach negative values. Furthermore, as the transverse damper was not initially fully bunch-by-bunch, more octupole current was required for low chromaticities [10]. The change in the octupole sign was finally found not to be helpful from both measurements and simulations (as can be seen from Fig. 4, where the same stability diagram is predicted for the most critical bunch and in the region of interest, i.e. for the negative real tune shifts which are expected from the impedance model) [11]. However, a positive sign is predicted to be much better for the case of the nominal configurations (see Fig. 4), and this is why the positive sign of the octupoles is used during Run 2.

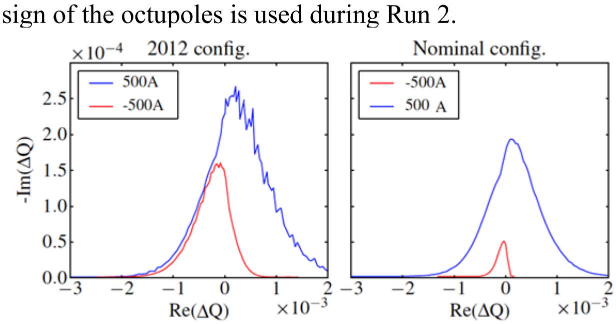

Figure 4: Comparison of the stability diagrams for the worst bunch at the end of the squeeze for each polarity of the octupoles, in 2012 and nominal configurations [11].

The main lesson learnt for the future was to better study the interplays between (all) the different mechanisms in a machine like the LHC. A lot of work has been done over the last few years (see for instance Ref. [12]) with in particular the proposed mechanism of the three-beam instability (both beams with an electron (e-)cloud) [13], the detailed analysis of the transverse mode coupling instability of colliding bunches [14] and the proposed mechanism of a modification of the stability diagram by

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some beam-induced noise [15]. To be able to learn more on stability diagrams from beam-based measurements, Beam Transfer Measurements (BTF) should be performed.

2015

In 2015, we restarted the LHC at 6.5 TeV (instead of 4 TeV in 2012) and the goal of this first commissioning/exploratory year of Run 2 was to established operation with the nominal 25 ns bunch spacing beam, anticipating difficulties with the beam-induced e-cloud.

Impedance-Induced Transverse Beam Instability

After the experience of Run 1 it was decided to start with the positive sign of the Landau octupoles and to study in detail the effect of chromaticity on the transverse beam instabilities, starting first with a single bunch. A summary of these measurements, compared to the predictions from the DELPHI code [16,12], is depicted in Fig. 5(upper) [17]. Three regions can be identified. In the region of interest for the operation, Q' > ~ 2, a good agreement was reached between predictions and measurements. In particular it can be seen that an octupole current of ~ 100 A was always sufficient to stabilise the bunch. The other regimes are discussed in Ref. [17].

Destabilising Effect of E-cloud

After having performed the study with a single bunch we decided to perform the same study with a train of 72 bunches, for a chromaticity of Q' ~ 7, knowing that the beam stability predictions from simulation are the same for a multi-bunch beam for a perfect damper with a sufficiently high gain. Two series of measurements were performed and the results are shown in Fig. 5(lower). During the first measurements a much higher octupole current than predicted from impedance (by a factor ~ 5) was required to stabilise the beam, while during the second measurements, a current compatible with the predicted value was measured. After detailed analysis, it was found that the first instability was certainly due to e-cloud (or at least due to the interplay with e-cloud) as the synchronous phase shift along the batch was quite high (~ 0.8 deg), revealing that a significant amount of e-cloud was still present in the machine [18], while during the second instability, the synchronous phase shift along the batch was much lower (~ 0.3 deg) [17].

Destabilising Effect of Linear Coupling

Due to e-cloud and the significant values of both chromaticities and octupole current which are required to stabilise the beam at injection, incoherent losses were observed and the working point at injection needed to be optimized [18]: it was moved from (0.28,0.31) to (0.275,0.295), essentially to move away from the third integer (0.33) resonance. This worked well but the distance between the two tunes reduced from 0.03 to 0.02 and when the Laslett tune shifts were not corrected during the injection process, the two tunes got even much closer (~ 0.009), which led to instabilities, which are believed to be due to linear coupling [19].

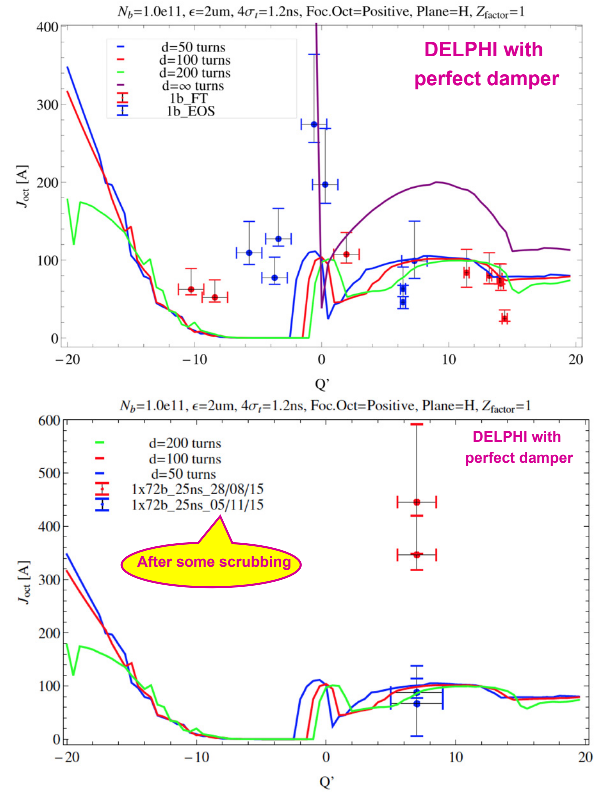

Figure 5: Stabilising octupole current vs. chromaticity: (upper) comparison between single-bunch measurements (dots: in red on the high energy flat-top and in blue at the end of the squeeze) and simulations (several curves depending on the transverse damper gain, assuming a perfect fully bunch-by-bunch damper); (lower) same as upper but with a train of 72 bunches spaced by 25 ns [17].

Beam Transfer Function (BTF) Measurements

A first stability diagram has been deduced from BTF measurements at injection [20]. The next step will be to fully understand the calibration factor as well as other interesting observations already reproduced by simulation but not yet fully understood [20].

Actions Taken

High chromaticities (~ 15) and about maximum octupole current were needed to keep the beam stable. As it was found that e-cloud can lead to instabilities also at high energy, a detailed simulation campaign was started to study the effects of the electrons from the arc dipoles and quadrupoles but also from the interaction regions. A detailed analysis of the effect of linear coupling on transverse beam instabilities was also started with a single bunch at high energy. With the new injection working point, both the Laslett tune shifts and the closest tune approach (called $|C^-|$) should be always corrected to avoid possible instabilities induced by linear coupling. The measurement of the $|C^-|$ at injection during the second half of 2012 revealed quite some high values [21]. Finally, the BTF measurements started to be benchmarked. This work

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should continue as it opens the possibility to study the stability diagram and its evolution with time to detect possible deformations, which could explain a loss of transverse Landau damping.

Lessons Learned

While in 2012 the machine was operating at 4 TeV with the 50 ns beam and in 2015 it was operating at 6.5 TeV with the 25 ns beam, in both cases high chromaticities (~ 15) and almost maximum octupole current were needed to stabilise the beam. While in 2012 it is still not completely clear why such high values were needed, it was clear in 2015 that an important e-cloud was still present at high energy and that it could drive the beam unstable. Furthermore, linear coupling should be studied in more detail during all the LHC cycle.

2016

2016 is a year of production and we applied the lessons learned during 2015: (i) the injection working point has been further optimized to (0.27,0.295); (ii) the Laslett tune shifts at injection have been corrected automatically; (iii) high chromaticties (~ 15) have been used during all the cycle; (iv) almost the maximum octupole current has been used at high energy and (v) linear coupling has been corrected during the cycle.

Destabilising Effect of Linear Coupling

Linear coupling can be a problem for beam stability because it can lead to a loss of transverse Landau damping. A simple model was used in Ref. [22], using an externally given elliptical spectrum, no transverse damper, etc. A detailed simulation campaign was performed for the LHC at 6.5 TeV with the pyHEADTAIL code [12], including the impedance model, the transverse damper, chromaticity and octupoles [19]. As the simulations were very time consuming, they were performed for a single bunch of $3\ 10^{11}$ p/b (still below the Transverse Mode Coupling Instability threshold). It can be seen from Fig. 6 that as the (decimal) tune separation Q_{sep} approaches the value of the closest tune approach, the required octupole current to stabilise the bunch becomes as large as ~ 4 times the required octupole current without linear coupling.

After the detailed simulation campaign, a dedicated measurement was performed in the LHC at 6.5 TeV, where two instabilities due to linear coupling could be observed. The first one revealed a remaining bump in the closest tune approach during the betatron squeeze around ~ 2 m, which led to a stabilising octupole current ~ 4 times higher than the uncoupled threshold [19]. A second measurement was then performed at flat top before the betatron squeeze, with the nominal injection tune, increasing the closest tune approach to $|C^-|$ ~ 0.01 and reducing the tune separation in steps. Here again, a much larger octupole current (by a factor ~ 4.4) was found to be necessary to stabilise the bunch in the coupled case. Renormalising the beam parameters, this case corresponds to the red star in Fig. 6.

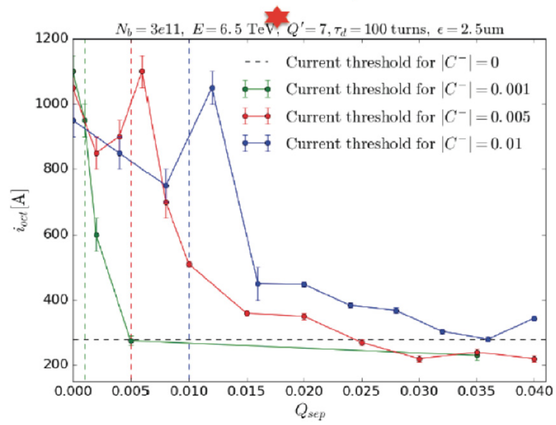

Figure 6: pyHEADTAIL [12] simulations of the stabilising octupole current vs. the (decimal) tune separation for a single bunch of $3\ 10^{11}$ p/b within 2.5 μm normalized rms transverse emittance interacting with the LHC impedance at 6.5 TeV with a chromaticity Q' = 7 and a transverse damper with a damping time of 100 turns [19].

In Collision: "pop corn" Instability

The LHC is currently operating with slightly more than 2000 bunches with a beam-induced heat load (due to e-cloud) close to the limit from the cryogenics capacity (160 W per half cell), meaning that a lot of electrons are still present in the machine [18]. And since the number of bunches reached ~ 600 bunches, the maximum octupole current and chromaticities of ~ 15 were not enough to stabilise the beam. Indeed, an instability has been observed in stable beam after few hours (see Fig. 7), which does not lead to beam losses but to transverse emittance blow-up (up to a factor ~ 2), only in the vertical plane of both beams and at the end of the trains of 72 bunches (where the bunch intensity is in fact the smallest due to some losses mainly at injection).

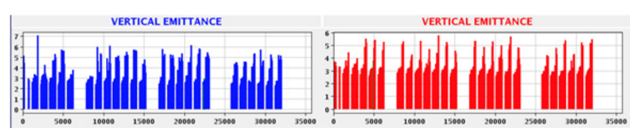

Figure 7: "Pop corn" instability observed in stable beam after few hours, despite the maximum octupole current and the high chromaticities (~ 15).

This instability clearly exhibits some signs of e-cloud and a possible mechanism was proposed [18]: when the intensity decreases a central stripe of electrons develops (between the two usual stripes observed in dipoles) where the density can become sufficiently high (in the order of 10^{12} e^-/m^3) to drive the beam unstable, without changing the total heat load [23]. Indeed, some past simulations, performed at 3.5 TeV, revealed that for an e-cloud density of $6\ 10^{11}$ e^-/m^3, the amplitude detuning from the octupoles was not sufficient to damp this vertical single-bunch instability [24] and that the effective knob was the chromaticity (more than ~ 15 units were needed), as already observed in the past at injection [25].

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Actions Taken

Linear coupling was corrected all along the cycle and in particular during the betatron squeeze. The Laslett tune shifts are now corrected automatically at injection. The vertical chromaticities have been increased by ~ 7 units in stable beam (to reach values of ~ 20-25), which almost completely suppressed the vertical emittance blow-up.

Lessons Learned

Linear coupling has to be well corrected all along the LHC cycle to avoid using too much octupole current. Even in the presence of a large tune spread in stable beam (due to head-on) the beam can become unstable. Fortunately the beam could be stabilised by increasing considerably the vertical chromaticities (to values as high as ~ 20-25), which still leads however to sufficiently good lifetimes: a high chromaticity does not seem to be an issue for the current LHC.

FUTURE

The LHC just reached the design peak luminosity of 10^{34} cm^{-2} s^{-1} [26] at 6.5 TeV and with about 25% less bunches than nominal. In HL-LHC, the bunch brightness should be increased by a factor almost 3 and transverse beam stability might become a limitation in the future: (i) will we have enough octupole current to stabilise the beam (an RF quadrupole was proposed to enhance the beam stability if needed [27])?; (ii) will we be able to use these high chromaticities in the future and how will this impact the beam lifetime and the minimum crossing angle which can be used (even if very encouraging results were recently obtained [28])?

Impedance-Induced Transverse Beam Instability

A detailed HL-LHC impedance model has been developed, and the related single-beam stability predictions are shown in Fig. 8 (for the most critical case of a transverse profile cut at ~ 3.2 σ [19]), where it can be seen that even if the impedance is a factor ~ 2 higher than the model, there should be enough octupole current. However, linear coupling should be well corrected all along the cycle, and all the sources of stability diagram deformation should be identified and the deformations minimized.

Beam-Beam

During the collision process, the stability diagram is reduced at two locations, at ~ 6 σ and ~ 1.5 σ, as can be seen in Fig. 9. It is worth reminding that no instability was observed at the minimum of the stability diagram during the regular operational fills. However, the recommendation has been made to go from 2 σ to 1 σ in less than 1 s (i.e. faster than the predicted instabilities) [19].

E-cloud

The main issue for the current LHC operation and for the future seems to be the e-cloud. Will we succeed to remove all the electrons from the dipoles? What is / will be the effect on beam stability? What about the remaining electrons in the quadrupoles? These questions are currently being addressed.

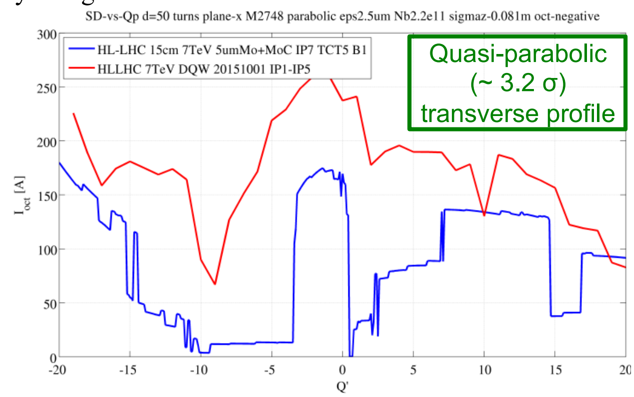

Figure 8: Single-beam stability predictions for HL-LHC at high energy (with, as foreseen, negative amplitude detuning from the Landau octupoles): without crab cavities (in blue) and with crab cavities (in red) [19].

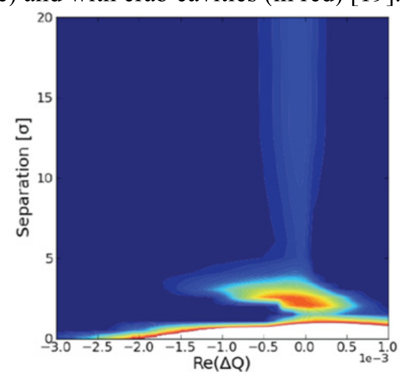

Figure 9: Evolution of the stability diagram during the collision process for the baseline scenario but with crab crossing off (similar picture with crab crossing on) [19].

CONCLUSION

The LHC is running very well, recently reaching the design peak luminosity [26]. However, transverse instabilities are a concern to push the performance further and despite the lot of progress made over the last years we still need to (fully) understand all the reasons for which, since 2012, we need to use at high energy the maximum octupole current and high chromaticities (~ 20-25 in 2016). Linear coupling between the transverse planes has been identified as a possible detrimental mechanism, which can considerably increase the required stabilising octupole current. E-cloud has also been clearly identified as a possible detrimental mechanism (also) at high energy, which can considerably increase both the required stabilising octupole current and the chromaticities. A simulation campaign has been started to try and better understand the mechanisms involved.

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