HUMP: HOW DID IT IMPACT THE LUMINOSITY PERFORMANCE AND STATUS


Abstract
The status of the measurements performed to characterize and identify the origin of the so-called hump will be presented as well as its impact on beam performance and the countermeasures found to mitigate its effects. The directions for future investigations will be outlined.

INTRODUCTION
Since the 2009 start-up with beam, tune spectra have evidenced the presence of a source of external excitation (so called “hump” because of its broad-band structure in the tune spectrum) mostly affecting Beam 2 and to a lesser extent Beam 1 [1]. The observed excitation was visible mainly in the vertical plane after correction of the machine coupling.

The main characteristics of the hump are summarized below [1][2][3][4]:

- the signal is mainly visible in the vertical plane for Beam 2;
- no dependence of the hump frequency on momentum offset or tune variation;
- the frequency of the hump is changing with time sometimes sweeping a large frequency span;
- there is a clear frequency correlation between the hump frequencies observed in the vertical plane for Beam 1 and Beam 2;
- the amplitude of the oscillation decreases with the inverse of the beam momentum;
- no evident dependence on the optics at the experimental straight sections has been observed (i.e. no evident dependence of the amplitude of the hump during the squeeze of the optics in IR1, IR2, IR 5 and IR8) has been observed;
- the amplitude of the signal on beam 2 does not depend on the presence of beam 1;
- blow-up of the vertical emittance is observed when the vertical tune is moved on top of the hump frequency (see Fig. 1).

The above observations are consistent with an oscillating horizontal dipolar field with amplitude independent from the energy of the beam and variable frequency.

During the 2010 run systematic tests have been performed to determine/exclude the possible origin of the above phenomena. The sources below can be excluded as a result of the tests conducted [1][2][3][4]:

- experimental magnets and compensators in all the four experiments;
- transfer line magnets (including injection septa);
- spool pieces (skew sextupole, octupole and decapole);
- transverse feedback;
- RF cavities;
- injection kickers;
- GSM or Fire Brigade Radio Network in the tunnel;
- triplet beam screen cooling (consistent with observations during the squeeze).

EFFECTS ON LUMINOSITY
At injection the hump is responsible for the blow-up of the vertical emittance observed during the injection plateaus (see Fig. 2). The blow-up rate depends on the distance of the hump frequency from the tune sidebands \((n\pm Q)f_{rev}\) where \(Q\) is the tune, \(f_{rev}\) is the revolution frequency and \(n\) is an integer.

Although the relative emittance blow-up due to the hump at top energy (3.5 TeV) is smaller than at injection (450 GeV) in collision beam-beam acts as a strong non-linear lens and oscillations induced by external excitation will de-cohere faster than at injection leading to the generation of tails and to losses.

The hump excitation can also drive beam-beam coherent modes leading to losses. Faster decrease in intensity and lower lifetime have been observed with ions and protons when no transverse feedback was operated in collision.

Fig. 1: Beam size evolution (red) vs. time when the vertical tune frequency (orange) is varied. The amplitude of the vertical oscillation (green) reached its maximum when the tune overlaps the hump tune (0.304). Courtesy R. Steinhagen.
Fig. 2: Vertical emittance of beam 2 versus time during injection. The measurement of the vertical emittance of the first bunch injected shows a linear increase at a rate of 1.5 μm/hour. Courtesy M. Meddahi, F. Roncarolo.

Fig. 3 shows the time evolution of the hump frequency while in collision. The vertical tune line (at 0.32) is artificially suppressed and indicated by a vertical line for convenience.

The hump frequency oscillates very close to the tune frequency and approximately two hours after the start of the acquisition (08:45 in the plot) its average frequency overlaps the tune frequency. When the overlap is largest beam losses appear as shown in Fig. 4.

No evident change of the beam size is visible at that time although a continuous slow increase of the vertical beam size is visible. Likely tails are generated which are lost at the collimators (see Fig. 5) with no significant change of the core size.

MITIGATION MEASURES AND NEXT STEPS

In parallel to the search for the origin of the hump, mitigation measures have been studied and implemented in order to damp this external excitation by means of the transverse feedback, first of all at low energy where the relative emittance blow-up is largest and in collision to avoid the excitation of beam-beam modes.

In presence of a source of emittance blow-up from a dipolar external excitation leading to an emittance blow-up rate \( (d\varepsilon/dt)_{\text{w/o fdbk}} \), the emittance blow-up rate when a transverse feedback is used to damp the external excitation, \( (d\varepsilon/dt)_{\text{w fdbk}} \), can be expressed as a function of the gain \( g \) of the transverse feedback and of the r.m.s. noise \( X_{\text{noise rms}} \) at the input of the power part of the feedback [5]:

\[
\frac{d\varepsilon}{dt}_{\text{w fdbk}} \propto \frac{\Delta\varepsilon_{\text{rms}}}{g^2} \left( \frac{d\varepsilon}{dt} \right)_{\text{w/o fdbk}} + \frac{f_{\text{r.m.s.}}}{2B_{\text{eff}}\varepsilon_{\text{rms}}} X_{\text{noise rms}}^2
\]

for \( \Delta\varepsilon_{\text{rms}} < g < 1 \)
where $\beta_{\text{BPM}}$ is the $\beta$ function at the monitor used for the measurement of the beam position on a turn-by-turn.

For that reason it is necessary to operate the feedback at high gain and to reduce the noise of the detection module of the feedback. After summer 2010 a resolution of 1-2 $\mu$m could be achieved in the measurement of the turn-by-turn and bunch-by-bunch position used for the transverse feedback [6] allowing to see the hump signal at least when its frequency is close to the tune frequency. Figure 6 and 7 show the effectiveness of the transverse feedback in dumping the hump line when its gain is increased to -10 dB or higher (0 dB corresponds to the maximum gain achievable by the feedback). In Fig 6 the hump frequency is visible at ~0.29 and it is dumped when the gain is increased from -24 dB to -10 dB. The two bands appearing symmetrically around the tune line when the damper is operated at high gain are delimiting the range of frequencies at which the feedback is working in a stable regime [6]. No significant blow-up due to the transverse feedback has been observed also in this regime.

Fig. 6. Vertical tune spectrum for beam 2 for different gains of the transverse feedback. The vertical tune is set to 0.31.

A similar behaviour is seen for Beam 1. In this case the hump frequency is sweeping the tune spectrum and crossing the tune line twice. The reduced excitation for the higher damper gain is clearly visible.

Following the noise reduction campaign on the transverse damper pick-ups and given the positive results of the above described tests, the machine has been operated with the feedback at high gain at injection. The gain was then reduced before starting the ramp to have enough residual excitation for the tune feedback to track the tunes and correct them during the ramp. A sketch of the damper gain during the machine cycle is shown in Fig. 8. The damper was switched off before starting the squeeze and it was switched on again at the end of the squeeze before going in collision. No time was available during the run to commission the operation of the transverse feedback during the squeeze.

Operation of the transverse feedback has allowed colliding beams with emittances below nominal and with emittance blow-up limited to 20-30% during injection and ramp by the end of September.

Optimization of the gain has not been done in collision yet, furthermore noise levels are more critical at high energy in terms of relative emittance blow-up as the physical emittance is smaller at high energy. So far the transverse feedback has been operated at low gain in collision and some effects of the hump are still visible in that phase when the hump frequency is crossing the tune line, as shown in Fig. 9. In that case a reduction of the specific luminosity is observed at the same time indicating an increase of the beam size.

The noise properties of the transverse feedback system are being studied and improvements are going to be proposed for implementation at the latest during the next long shut-down [6].

Extensive analysis of the time evolution of the frequency of the hump over long periods is ongoing and has shown that the hump is always present but with a different frequency pattern and for that reason it can have a different impact on the beam quality according to the distance that the hump frequency has from the tune.
Fig. 9. Tune spectrum versus time. The hump line initially just above the vertical tune crosses the tune line (0.32) while in collision. The horizontal tune line is also visible (0.31). The time interval from 17:30 to 20:00 on 22/09/2010 is shown (Fill #1364).

Fig. 10. ATLAS Specific luminosity for fill #1364.

Fig. 11 shows the frequency evolution of the hump over time intervals of few hours each, in different periods of the run. There is not a region of the tune spectrum which is completely immune from the hump and sudden variations in the time evolution of the hump frequency have been observed and are presently under investigations in order to determine possible correlations with external events or actions on the machine hardware.

A dedicated fixed display showing the evolution of the hump spectrum as a function of time has been implemented in the control room to facilitate the correlation between these sudden variations in the frequency evolution of the hump and any possible action on the machine or on its technical systems. A typical snapshot of the fixed display is shown in Fig. 12. In this case (coast #1372) the hump frequency is slowly varying very close to the vertical tune frequency over a period of two hours and lifetime could have been improved by shifting slightly the working point to minimize the overlap between the hump frequency and vertical beam 2 tune. Systematic use of the fixed display at injection or in collision to optimize the working point for beam 2 when the hump frequency is slowly varying is recommended for the 2011 run.

Fig. 11. Time (in seconds) evolution of the hump frequency during different periods of the run. The intervals of time when no signal was observed (e.g. in the
plot in the middle) correspond to periods with no beam circulating in the machine.

**Fig. 12.** Snapshot of the hump frequency display: raw data (top), after suppression of the frequencies which are constant in time (bottom) (Courtesy R. De Maria and M. Terra Pinheiro Fernandes Pereira).

**RECENT PROGRESS**

**Beam measurements**

All the measurements described so far were performed with the tune measurement system (BBQ) [7] which allows one acquisition per turn of the average beam position. The frequency of the hump cannot be determined univocally but it can be any of the sidebands of the revolution frequency \((\pm Q_{hump} + n)f_{rev}\) with \(0< Q_{hump} < 0.5\) where \(Q_{hump}\) is the frequency of the hump measured by the BBQ in units of the revolution frequency and \(n\) is an integer. BPMs and the Schottky monitor have not enough resolution to discriminate the amplitude of the oscillations induced by the hump which are in the micrometer range when the hump is close to the tune frequency.

In the last part of the 2010 run (second half of November) turn-by-turn/bunch-by-bunch position measurements have been possible with the transverse damper pick-ups and measurements have been performed during ion operation with ion filling schemes with a minimum bunch spacing of 500 ns. This has allowed extending the range of the measurement of the real frequency of the hump up to 1 MHz. The measurements are being analyzed in detail but the preliminary results evidence lines at the following frequencies \(f_0\): 243 kHz, 335 kHz, 487 kHz (this is likely the second harmonic of the first frequency), 532 kHz (see Fig. 13).

**Fig. 13.** Frequency spectra from bunch-by-bunch measurements performed with the ion beam (Courtesy R. De Maria).
Given that the minimum spacing among bunches is 500 ns the above frequencies could be aliases and the real frequency of the hump could be any value \( f = \pm f_0 + n \times 2 \) MHz. If confirmed, the above observations would rule out UPS (Uninterruptible Power Supplies) as the possible origin of the hump.

So far no systematic and monotonic variations of the average tune of the hump have been evidenced during the ramp (see Fig. 14). This would be the case if the frequency of the hump is not correlated with the RF frequency and it is a sufficiently large harmonic of the revolution frequency as the sampling frequency of the turn-by-turn position is varying during the ramp. For the lead ion beam the RF frequency sweep during the ramp is largest as compared to that of the ion beam and amounts to 5513 Hz, corresponding to a sweep in revolution frequency of ~0.155 Hz. The frequency \( f \) of the hump is therefore smaller than 16.8 MHz assuming that we could resolve systematic variations of the hump tune larger than 0.02 during the ramp and that the frequency of the hump is not correlated to the RF frequency.

**Magnetic measurements**

Remote magnetic measurements by means of coils installed in the tunnel have been performed during the machine run and are continuing during the Christmas stop to attempt localizing the source of the hump (in a sector of the machine) and in general to determine all the possible sources of noise affecting the beam.

The comparison of magnetic and beam measurements performed in November 2010 show a very good agreement in the periodicity of the frequency evolution of the hump frequency and noise measured in the tunnel (See Fig. 15 - in this case in point 5), although the absolute amplitude of the variation does not correspond. At the time of the measurement the sampling frequency for the magnetic measurements was 200 kSamples/s and the quoted values of the frequencies could be aliases of higher frequencies.

Preliminary measurements conducted during the Christmas stop indicate that noise at frequencies of a few hundreds of kHz is visible (see Fig. 16).

**SUMMARY**

The hump affects luminosity performance due to blowup (particularly at 450 GeV). In collision it can excite beam-beam coherent modes or generate tails and therefore losses.

Priority has been given to implement mitigation measures: the transverse feedback has proven to be effective to mitigate these effects and as a result of that beams with emittances in the range of 2.5 micrometers could be regularly brought in collision.
The identification (and possibly eradication) of the origin remain the (challenging) goal of the ongoing analysis and measurements.

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REFERENCES