Non-linear beam dynamics tests in the LHC


Keywords: non-linear dynamics, detuning with amplitude, non-linear chromaticity, dynamic aperture

Summary

This note reports on the first tests of non-linear beam dynamics at the LHC. Their aim was to measure the non-linear chromaticity and detuning with amplitude as well as a possible correction of the second and third order chromaticity using the main dipoles’ spool pieces. A second objective was to start probing the dynamic aperture with dedicated measurements. As most of these measurements can be performed simultaneously in the two rings, it was decided to measure the dynamic aperture using Beam 1, while the detuning and non-linear chromaticity part was done on Beam 2. It is worth emphasizing that the non-linear chromaticity measurement, requiring a change of energy, couples the two rings. Thus, during this measurement the tests on Beam 1 had to be stopped.

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Non-linear Measurements at Beam 2

In parallel to the measurement of dynamic aperture of Beam 1, measurements of the non-linear chromaticity and detuning with amplitude, as well as an attempt of the second and third order chromaticity corrections were performed for Beam 2. The measurement of the non-linear chromaticity was done with the standard technique: measuring tunes for different values of RF frequencies. In this case tunes were measured with base-band-tune (BBQ) system [7, 8]. The correction of the second and third order chromaticity was attempted with knobs of octupole and decapole spool pieces (MCO and MCD) prepared prior to the MD. With the aperture kickers (MKA) the beam is excited in regular steps up to the maximum kick strength. For each kick the tune is calculated by a Fourier Transform of the turn-by-turn position data, and averaged over all BPMs. Hence the detuning with amplitude is determined [6].

AC dipole excitations were also recorded to allow for benchmarking of the two excitation techniques.

For these measurements of Beam 2, a single bunch with a small intensity between 0.8E10 and 1.2E10 was used. Tunes were adjusted to the nominal injection values of $Q_x = 64.28$ and $Q_y = 59.31$ and chromaticities were adjusted to 1.5 unit in both planes. All the octupoles and decapoles were pre-cycled prior to the MD and lattice octupoles (MO) were de-Gaussed and left turned off during the MD. Octupoles in spool pieces were set to zero field settings (see details in Sec. 1.1) but later used for the second order chromaticity correction.

The MD proceeded as follows:

- Measurement of the detuning with the aperture kicker
  - Simultaneous excitations on both planes
  - Excitation of horizontal plane only
  - Excitation of vertical plane only
  - Data acquisition with AC dipoles

- Non-linear chromaticity measurement and correction
  - Measurement of the non-linear chromaticity
  - Application of second and third order chromaticity corrections
  - Re-measurement of the non-linear chromaticity to verify the correction

- Re-measurement of the detuning with the aperture kicker with the second and third order chromaticity correction
  - Excitation of horizontal plane only
  - Excitation of vertical plane only
  - Simultaneous excitations on both planes
  - Data acquisition with AC dipoles
1.1 Measurement of Non-linear Chromaticity

The variation of the tune with the relative momentum offset is given by:

\[ Q \left( \frac{dp}{p} \right) = Q_0 + Q' \left( \frac{dp}{p} \right) + \frac{1}{2!} Q'' \left( \frac{dp}{p} \right)^2 + \frac{1}{3!} Q''' \left( \frac{dp}{p} \right)^3 + ... \]  

where \( Q' \) is the linear chromaticity while \( Q'' \) and \( Q''' \) are the second and third order chromaticity terms, typically produced by octupoles and decapoles respectively.

In 2010 and 2011 the non-linear chromaticity was measured several times and found consistently to have \( Q''_x \) values between -2000 and -3000 (at the lower end in 2011). This is approximately ten-fold larger than expected from the best LHC model we currently possess. In view of understanding this discrepancy simple knobs were designed to allow the correction of \( Q'' \) and \( Q''' \) by varying the powering of the fourth and fifth order spool pieces respectively. The two knobs were defined such that a constant increment in KSMOOTH was applied to the spool pieces in each arc, with a single knob unit corresponding to \( +1Q'' \) and \( +10'000Q''' \) for the second and third order knobs respectively. Details of the knobs are presented in Tab. 1.

Following an initial measurement of the uncorrected non-linear chromaticity the appropriate number of knob units to best compensate the observed \( Q'' \) and \( Q''' \) were calculated and applied to the respective spool pieces. The currents in the spools are also presented in Tab. 1.

<table>
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<tr>
<th>( Q'' ) Knob</th>
<th>Element</th>
<th>Knob (KSMOOTH)</th>
<th>Correction (knob units)</th>
<th>I before correction (A)</th>
<th>I with correction (A)</th>
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Table 1: Octupole and decapole spool piece settings before and after the \( Q'' \) and \( Q''' \) correction.

The octupole spool pieces in arcs 78 and 81 remain unpowered due to hardware issues. The knobs used for the experiment remain stored in the beta-beating section of the LSA database. It is also important to mention that the \( \pm 3 \text{ A} \) of these spool pieces are not the nominal ones but set such that
the fields are supposedly zero according to the hysteresis loops. The measured $Q''$ should therefore be due to the $b_4$ component of the dipoles only.

The $Q''$ correction requires to add 6 A to all MCOs which is twice their absolute standard value. At first sight one could conclude that the main dipoles might have an un-compensated $b_4$ component. On the other hand, one has to consider the rather large hysteresis at the low excitation of the MCOs. Further studies will have to clarify the source of the octupolar term that excites the large $Q''$. The decapolar terms seem slightly smaller than expected: Tab. 1 demonstrates that the values which correct the third order chromaticity are 25% lower than given by the local correction.

Fig. 1 shows the $Q''$ and $Q''''$ measurements before and after correction, on the left and right side respectively. Both second and third order chromaticity terms are almost perfectly compensated and are close to the model expectations.

![Graphs showing non-linear chromaticity measurements before and after correction.](image)

Figure 1: Non-linear chromaticity measurement before and after the $Q''$ and $Q''''$ corrections at left and right respectively.

It remains to be understood why the measured $Q''$ values before correction remain rather constant independent of the fact that the $b_4$ spool pieces are put to zero field or set to nominal values to correct the $b_4$ of the dipoles (see comparison with measurements from the 10th of June as shown in the minutes of the Fidel working group [9] held on the 5th of July 2001).

<table>
<thead>
<tr>
<th>$Q''$</th>
<th>$Q''''$</th>
<th>$Q''''$</th>
<th>$Q''''''$</th>
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<tr>
<td>Before Correction</td>
<td>-2140</td>
<td>740</td>
<td>-1914000</td>
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<tr>
<td>After Correction</td>
<td>-720</td>
<td>-183</td>
<td>-327000</td>
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Table 2: Measured non-linear chromaticities
1.2 Detuning with Amplitude

The $Q''$ correction is mainly correcting the local $b_4$ component of the main dipoles. One should therefore expect that other octupolar effects are reduced as well and in particular the detuning with amplitude. The easiest way to demonstrate this effect is to compare the decoherence of large kicks for both machine configurations. Indeed Fig. 2 shows that the decoherence for the un-corrected machine (red crosses) is by far more rapid than after the correction (blue stars). In conclusion, we have demonstrated that we can make the motion of the protons almost linear in the LHC.

More relevant is the measurement of the detuning with amplitude. Fig. 3 shows the three detuning terms before the correction (red) and after (blue). The upper left graph shows that the horizontal detuning is largely reduced while the vertical detuning (lower right) has been much smaller but remains small despite the fact that the sign of the detuning has been changed. As expected the cross-terms are about equal (the third term) and a sizable reduction is also evident. Results of the fit to the measured data are presented in Tab. 3.

![Figure 2: The decoherence of a 4.8 $\sigma$ kick for the un-corrected machine (red crosses) and after the $Q''$ and $Q'''$ correction (blue stars).](image)

<table>
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<tr>
<th>Before Correction</th>
<th>$Q_x/2T_x$</th>
<th>$Q_y/2T_y$</th>
<th>$Q_x/2T_y$</th>
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<td>($\pm 0.0015$)</td>
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<th>After Correction</th>
<th>$Q_x/2T_x$</th>
<th>$Q_y/2T_y$</th>
<th>$Q_x/2T_y$</th>
<th>$Q_y/2T_x$</th>
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<td>($\pm 0.0005$)</td>
<td>($\pm 0.0017$)</td>
<td>($\pm 0.0008$)</td>
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Table 3: Measured detuning with amplitude before and after correction of the non-linear chromaticity. In brackets the errors of the measurements.

2 Dynamic aperture measurements at Beam 1

The basis of the proposed test to probe the dynamic aperture is the inverse logarithm scaling law for dynamic aperture [1, 2, 3]. This scaling law, derived from tracking data, has been recently used to derive a possible relation between the intensity evolution and dynamic aperture [4]. So far, no particular lifetime issues were observed at injection, thus indicating that the dynamic aperture should be comparable to the mechanical one. This suggests that a more effective strategy consists of reducing artificially the dynamic aperture by acting on some of the non-linear circuits present in the ring. In any case, the injected beam needs to be blown-up in order to have enough particles probing high amplitudes and hence experiencing non-linear effects. This is certainly not the only technique to measure the dynamic aperture and in future also other approaches will be attempted.

In light of these considerations, the strategy was as follows:

- The machine is prepared in a configuration that is similar to the operational one apart from the Landau octupoles that are set to zero current after having applied a de-Gaussing cycle. All
collimators are put in parking position\textsuperscript{1} with only the primary devices set to 12 $\sigma$ in order to shadow the machine aperture that was measured to be larger than about 13 $\sigma$ (the triplets being beyond 14 $\sigma$).

- A pilot bunch (operational normalised emittance, i.e. about 2 $\mu$m, about $1 \times 10^{10}$ p) is injected after careful correction of the coupling.
- Repeated kicks applied with the aperture kicker to blow-up the beam size until losses are observed.
- The losses are recorded and analysed off-line for studying the time-dependence.

This procedure has been repeated by changing the settings of the octupolar spool pieces with settings pre-computed and based on numerical simulations with the aim of reducing artificially the dynamic aperture. While the $b_4$ in the dipoles features alternating sign between the two apertures, the additional strength from the MCOs had a fixed sign all along Ring 1. This generates strong chromatic effects, as seen in Fig. 4.

\textsuperscript{1}It turned out that the TCDQ was left at 8 $\sigma$.

Figure 3: Measured detuning of amplitude including cross-terms (upper and lower for horizontal and vertical plane respectively). The labelling before and after refers to the $Q''$ and $Q'''$ correction.
Figure 4: Tune vs. momentum offset (horizontal - left, vertical - right) as computed with the PTC model for the nominal configuration and for the variants as used in the experiment. The latter leading to large second order chromaticity $Q''$.

It is worth emphasising that a similar scan with the decapolar correctors, although originally in the plans of the MD, could not be performed due to a break-down of the Beam Energy Tracking (BET) in the SPS that prevented extracting Beam 1 to the LHC from about 9:30 until the end of the MD.

The plot shown in Fig. 5 summarises the evolution of the test. Until about 5:30 the beam was prepared and in particular the use of the aperture kicker to blow up the beam was tested.

Figure 5: Summary plot of the test performed during the dynamic aperture probing. The intensity is shown together with the bunch length and the strength of the MCOs.
Then, using the nominal settings of the MCOs, namely those that are supposed to compensate for the $b_4$ component of the main dipoles, the beam has been excited until the loss limit was reached resulting in decay of the intensity.

Just before 7, the MCOs have been changed resulting in another clear intensity decay. For the following steps of the strength of the MCOs the same beam was kept to avoid the need for injecting a fresh bunch. For each MCO setting a clear intensity decay has been observed. In particular, for the configurations with MCOs at $-40$ A and $-60$ A, respectively, we have noticed a reduction in bunch length$^2$. This correlates well with the large negative second order chromaticity. Lastly, the MCOs were moved towards positive currents. During the transient between negative and positive values, a sudden drop in intensity was observed by looking at the details of the intensity evolution.

The evolution of the beam size is monitored via the wire scanner and the synchrotron light monitor. The latter provides a continuous beam size and profile measurement that was regularly cross-calibrated using the wire scanners. The evolution of the beam emittance for the horizontal and vertical planes is shown in Fig. 6.

Figure 6: Emittance (horizontal - upper, vertical - lower) and intensity evolution during the dynamic aperture measurements. The steps in the emittance evolution are generated by the kicks applied by the aperture kicker. For the wire scanner measurements, both the In and OUT scanner results are shown.

The originally round beam is rather well preserved even after the multiple kicks applied with the aperture kicker. The steps in the emittance evolution are indeed the sign of the kicks. In general, wire scanner measurements were performed after the injection and after each kick in order to verify the

$^2$The resolution of the bunch length measurement is 125 ps [5].
cross-calibration of the two instruments. The large differences after the kicks between the results of the two instruments might be due to the non-Gaussian shape of the beam distribution after kicking it. In particular, the non-Gaussian shape explains the apparent incoherent result concerning losses in between 6:45 and 7:45. Indeed, during this period two intensity decays can be observed in Fig. 5. The first decay seems faster than the second one. On the other hand, from Fig. 6 one would conclude that the beam size (or emittance) is in reality smaller for the first loss period, which is counter-intuitive. In fact, detailed inspection of the measured profiles with the wire scanner (see Fig. 8) reveals that during the first loss period the beam is large. However, the sigma fits underestimates the actual beam sigma, in particular for the vertical plane.

The situation is even clearer in Fig. 7, where the evolution of the transverse profiles as measured by the BSRT is shown. The profiles have been normalised to their integral. Indeed, while the core is smaller for the data around 6:45 than for the situation around 7:45, the tails are in fact larger for the case around 6:45. In particular this is more evident for the vertical plane. In the off-line analysis it is planned to use the complete information about the beam profile rather than just simple Gaussian fits.

The beam losses correlated to the intensity decay have been monitored by means of the BLMs. The two aperture limits in the machine are the primary collimators (TCP) and the TCDQ and indeed the losses are concentrated at those locations as seen in Fig. 9. It is worth emphasising that the TCDQ is a horizontal device. Hence, nothing can be stated about possible losses in the vertical plane.

The losses at the TCDQ depict a rather smooth decay rather than an instantaneous drop of intensity. This observation seems to indicate that the losses are due to slow non-linear (chaotic) processes instead of an intensity cut-off by a mechanical aperture in the machine. In fact, diffusive-like phenomena would produce continuous losses. In some cases the first spike followed by the long lasting losses might be the sign that some beam was suddenly scraped off and then the diffusion takes over and generate slow losses.

The losses distribution over the whole machine circumference at various times are reported in Fig. 10. The losses are distributed evenly over the ring apart from a sharp spike at the location of the TCDQ. For all six MCO settings the intensity decay appear rather similar except for losses at the collimators in IP2 for the first two loss maps.

Figure 7: Evolution of the horizontal (left) and vertical (right) beam profiles as measured by the BSRT. The colour scale represents the amplitude of the measured profile. in order to take into account the difference in total intensity, the profiles have been normalised to their integral.
Figure 8: Beam profiles for the horizontal (first two rows) and vertical plane (second two rows), respectively. The first and third rows refer to the profile measured at 6:45, while the second and fourth rows represent the profiles measured at 7:45. The left column refers to the IN scan, while the right column represents the OUT scan.
Figure 9: Evolution of beam losses with time on the primary collimators (upper graph) and TCDQ (middle graph) during the dynamic aperture tests. The intensity evolution as measured by the fast BCT is also reported (lower graph). A zoom of a specific loss event for the TCDQ is shown in middle right graph.
Figure 10: Loss maps during the dynamic aperture tests. The time of each loss maps is shown.
3 Conclusions

The first probing of the dynamic aperture was attempted in this MD. Data were collected concerning the intensity decay in presence of strong non-linear effects in view of fitting with the proposed scaling law. This analysis is in progress. A correlation between the overall losses and the bunch length has been observed in some cases. This could be explained by the strong impact that the MCOs had on the non-linear chromaticity. In this respect, in a future session it would be worth testing alternative configurations in which the signs of the MCOs are alternating. This would provide a first-order compensation of the octupolar effects, thus minimising the non-linear chromaticity.

The beam blow up by means of the aperture kicker proved to be less effective than foreseen. In particular it does not ensure the generation of a Gaussian-like beam distribution. The details of the actual distribution will need to be taken into account in the off-line data analysis. In a future MD a different approach might be tried out, based on the use of the transverse damper to excite the beam or the tune kicker.

Clearly, it would be also interesting to probe the non-linear dynamics generated by the MCDs, and a scan, that could not be performed during the last MD, should be planned.

The non-linear measurements went well beyond our wildest dreams rendering an almost linear LHC machine at half the expected dynamic aperture. This has been achieved with the simplest octupolar and decapolar knobs possible, i.e. varying all spool pieces with the same current. These knobs made it possible to correct the second and third chromaticity in one go without any iteration and exactly as predicted by the non-linear model!

We have a tremendous wealth of high quality BPM data that needs to be analysed and compared with the model predictions. In particular, we have two sets of data with medium and small content of non-linearities. For both sets we have BPM data up to $6 \sigma$ kicks with free oscillations (aperture kicker) and forced oscillations (AC-dipole). This will allow for a benchmarking of the two excitation techniques.

We cannot ignore to mention that during the MD we have been somewhat limited by the fact, that the aperture limit has been $8 \sigma$ at certain collimators. For the next MD we will need instead an opening of all collimators to $12 \sigma$ to allow a direct DA measurement once the kick strength of the aperture kicker will have been increased by a factor of two in the fall of 2011.

Acknowledgments

We would like to thank J.-J. Gras, R. de Maria, E. Shaposhnikova, and G. Papotti for help and fruitful discussions.
A  Speed-up of the Drive_God tool

SUSSIX [10] is a FORTRAN program for the post processing of turn-by-turn BPM data, which computes the frequency, amplitude, and phase of tunes and resonant lines to a high degree of precision through the use of an interpolated FFT. Analysis of such data represents a vital component of many linear and non-linear dynamics measurements; including that of the amplitude detuning described above. For analysis of LHC BPM data a specific version 

\texttt{sussix4drive}, run through the C steering code \texttt{Drive_God_jin}, has been implemented in the CCC by the beta-beating team.

Analysis of all LHC BPMs, however, represents a major real time computational bottleneck in the control room, which has prevented truly on-line study of the BPM data. In response to this limitation an effort has been underway to decrease the real computational time of the SUSSIX codes by parallelizing it. This has now been achieved, using the OpenMP API [11] to parallelize with respect to the independent analysis of BPMs. The pure FORTRAN version of SUSSIX was successfully parallelized, and this was then extended to the control room mixed FORTRAN and C implementation. OpenMP works by multithreading the C or FORTRAN following directives inserted into the code, the threads then map onto physical CPU cores in a multi-core machine. Figure 11 demonstrates the effect of this real time speed-up for a test case of real 1000 turn LHC BPM data, analysed to find 160 lines. The analysis was performed on a reserved 24 core machine \texttt{cs-ccr-spareb7} in the CCC. About a factor of 10 improvement in the real computation time has been realised. For the study of amplitude detuning the parallelized SUSSIX was utilised within the beta-beat GUI [12], and the tenfold time reduction was verified in practice. This technique could be of interest to other applications.

![Figure 11: Speed-up of Drive_GOD as a function of number of cores.](image-url)
References


