

LHC ONLINE CHROMATICITY MEASUREMENT - EXPERIENCE AFTER ONE YEAR OF OPERATION

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Abstract

Hardware and infrastructural requirements to measure chromaticity in the LHC were available since the beginning. However, the calculation of the chromaticity was mostly made offline. This gap was closed in 2015 by the development of a dedicated application for the LHC control room, which takes the measured data and produces estimates for the chromaticity values immediately online and allows to correct chroma and tune accordingly. This tool proved to be essential during commissioning as well as during every injection phase of the LHC. It became particularly important during the intensity ramp up with 25ns where good control of the chromaticity became crucial at injection. This paper describes the concepts and algorithms behind this tool, the experience gained as well as further plans for improvements.

INTRODUCTION

A very good control of chromaticity is critical for LHC operation to counteract instabilities and resulting emittance blowup. During standard operation a big part of this is achieved by model based feed-forward during injection and ramp [1, 2]. However, in numerous operational scenarios (e.g. commissioning periods, machine development, non-standard cycles), a manual way for the operations crew to check and correct chromaticity is indispensable.

Additionally, the measurement data for the feed-forward and for tuning the models have to be qualified and at the beginning of each filling of the LHC, the chromaticity is systematically checked by the operations team. Therefore, such means have to be quick and simple in order reduce turnaround time and operational mistakes, respectively.

Already in LHC run 1, a simple online chroma display was available, based on radial modulation. At the start of run 2, with the big amount of software changes on different layers, this display became dysfunctional and was not maintained anymore. To fill this gap, a more integrated application was introduced, which not only allowed measuring and tracking chroma through the cycle, but also allowed direct calculations of corrections and sending them to the hardware.

The following sections are describing the principles and features of this application, its usage and future improvements as well as some more general outlook on the future of LHC online chroma measurement.

FEATURES AND OVERVIEW

Figure 1 shows a screenshot of the LHC chroma application displaying traces of measured chroma during a ramp. The top panel of this application shows the actually measured chroma values, allows to set target values, calculate

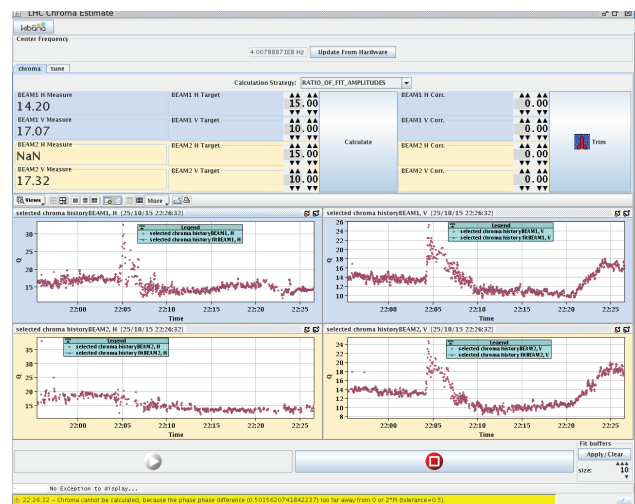


Figure 1: LHC Chroma Application, showing chroma traces throughout a ramp, dedicated chroma measurement.

corrections and send them to the hardware. The bottom panel of the application can display various traces of input- and calculated data:

- raw tunes,
- raw RF modulation signal,
- fits to both (see below) and
- calculated chroma values.

Further, the same application also allows to trim tune values (placed on a second tab).

Since no direct measurement of the chromaticity is yet available at the LHC, the chroma app follows the 'usual procedure' as if measuring the chroma manually: Changing the RF frequency (corresponding to an energy change) and measuring the tune change resulting from this energy change. Therefore, two signals are required: The frequency change (wrt the centered frequency) and the actual tune of the machine.

Raw Data Flow

While the RF frequency is a direct input to the machine and can therefore directly be acquired from the RF systems in high precision, the tune has to be derived (measured) from the transverse beam motions. The state-of-the-art devices to accomplish a high sensitivity tune signals are the so-called BBQ devices [3], which deliver a very good tune signal under various different conditions. Without going into the detailed complexity of the full LHC tune acquisition chain, we only want to mention here, that these are the same systems which are also used for the LHC tune realtime feedback systems. Several instances of such BBQ devices are available, which are pre-configured for different scenarios (mainly driven by

beam intensities). The different devices are selected by the control system during the different phases of operation and the feedback system feeds-through the signals of the actually selected device. For this reason, it proved to be a good choice to take the tune signal from the feedback system to be used in the chroma measurement application, since then always the 'good' signal is automatically selected. Figure 2 shows a sketch illustrating this concept.

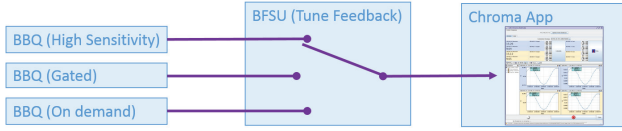


Figure 2: Overview of the tune data flow from the tune measurement devices up to the chroma measurement GUI.

In addition to the 'signal switching' the feedback device also provides functionality to easily modulate the RF frequency with a sine function. From the beginning, this was used in LHC run 1 already for an online chroma display. Another idea was also to have feedback based on these principles. However, this never became operational because a continuous shaking of the beam is undesirable. However, at injection, using pilot bunches, this concept proved to be useful as described in the following.

ALGORITHMS

The chromaticity Q' of the machine dictates a tune change ΔQ resulting from a momentum deviation $\Delta p/p$:

$$\Delta Q = Q' \frac{\Delta p}{p}. \quad (1)$$

The energy change $\Delta p/p$ is given by

$$\frac{\Delta p}{p} = \frac{\Delta f}{f} \frac{1}{\eta}, \quad (2)$$

with

$$\eta = \frac{1}{\gamma_r} - \alpha_C. \quad (3)$$

where Δf is the change in RF frequency, f denotes the on-momentum RF frequency, γ_r the relativistic gamma and α_C the momentum compaction factor of the ring. For reference, the relevant parameter values for the LHC are given in Table 1.

Table 1: Relevant Machine Parameters for Chroma Calculation in LHC

parameter	unit	value
α_C	[1]	$3.225 \cdot 10^{-4}$
f	[Hz]	400 788 860
γ_r (injection)	[1]	479.6

Version 0 - The Naive Approach

The simplest way to calculate the chroma is the inversion of Eq. (1). Using $Q(t) = Q_{om} + \Delta Q(t)$, this results in

$$Q(t) = Q_{om} + Q' \frac{\Delta p}{p}(t). \quad (4)$$

$Q(t)$ denotes the tune signal over time, and Q_{om} the on-momentum tune. In the initial version of the chroma application, an algorithm was implemented which, for each acquired tune value, calculated the momentum offset from the actual frequency and performed a linear fit to Eq. (4), using Q_{om} and Q' as free parameters. Figure 3 shows an example of such a fit.

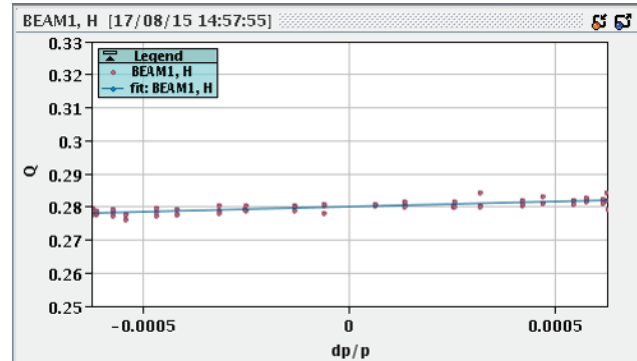


Figure 3: Example of a fit which was used to derive the chromaticity from the tune-slope.

This algorithm worked well as a first iteration and had the advantage that it was independent of the way how the RF frequency was changed (e.g. momentum trims in steps or automatic modulation). Nevertheless, it showed problems due to technical particularities in the acquisition chain: In cases where there were delays in acquiring either the RF frequency or the tune signal and thus the signals were misaligned in the order of a second, the derived chroma could not be trusted.

Version 1 - Sine Fits

To be independent of misalignments in time of the tune- and RF- modulation, the following algorithm based on harmonic fits was implemented: When using the RF modulation functionality, both the RF frequency and the tune signal follow harmonic oscillations:

$$\frac{\Delta p}{p}(t) = A_p \sin(\omega t + \varphi_p) + B_p, \quad (5)$$

$$Q(t) = A_Q \sin(\omega t + \varphi_Q) + B_Q. \quad (6)$$

A_p and A_Q denote the amplitudes of the $\Delta p/p$ and tune oscillations, respectively, φ_p and φ_Q the phases, B_p and B_Q an offset and ω the frequency of the modulation¹. Hereby B_p corresponds to an 'artificial' energy offset which can come from small RF trims at injection to center the orbit and B_Q corresponds to the on-momentum tune. The 4 parameters

¹ Typical parameters for modulating the RF frequency during a chroma measurement are e.g. $f = \omega/2\pi = 0.08$ Hz and $A_p = 0.0003$.

($A_{...}$, ω , $\varphi_{...}$ and $B_{...}$) for each of the above equations are determined by corresponding fits. Figure 4 shows example data for the evolution of the tune signal, together with its corresponding fit.

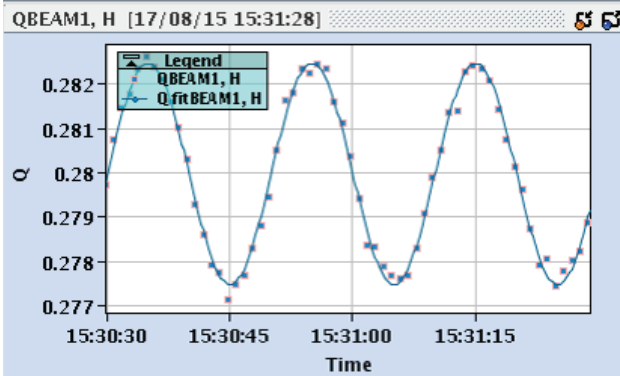


Figure 4: Example data of the tune acquisition and a sine fit to it.

Since the frequency ω is by definition the same in Eq. (6) and Eq. (6) and the RF signal is very precise, the value for ω from the fit to the $\Delta p/p$ evolution is used as an initial guess to the fit of the Q evolution.

Finally, the chroma Q' can simply be calculated as

$$Q' = \frac{A_Q}{A_p} \cdot \text{sgn}(Q') \quad (7)$$

with $\text{sgn}(Q')$, the sign of Q' being estimated as

$$\text{sgn}(Q') := \begin{cases} +1 & \text{if } \Delta\varphi = 0 \pm \varphi_{\text{lim}}, \\ -1 & \text{if } \Delta\varphi = \pi \pm \varphi_{\text{lim}}. \end{cases} \quad (8)$$

Hereby, $\Delta\varphi$ is simply the absolute difference between the two fitted phases, $\Delta\varphi = \text{abs}(\varphi_Q - \varphi_p)$ and φ_{lim} an (experimentally determined) tolerance².

Potential Improvements

The described algorithm proved to be stable in general. The most relevant improvement to be introduced in the near future is the proper automatic treatment of measurement outliers. The planned approach is to do a second fit, which would only include data points which are within a certain distance to the initial fit (e.g. below 3σ).

Another (similar) option which is considered is a second fit, taking into account again all data points but using weighting factors inversely proportional to the distance to the initial fit.

ARCHITECTURE AND TECHNOLOGY

The application is written in the java programming language as all the rest of the LHC control system GUI parts. While the user interface part is still written using swing technology, which is already deprecated at the time of writing, the backend part uses state of the art technologies and served

² In the current version we are using $\varphi_{\text{lim}} \approx 30$ deg.

as a usecase to probe several new technologies for their usage in further software projects. The most promising of them turned out to be RxJava [6].

RxJava allows provides a concept called 'reactive streams', which allows to implement dataflows within the application as streams which can be transformed and combined. This approach leads to a very clean, data-focused approach. Generalization of these concepts is currently ongoing and we are planning to reuse the same approach in new developments and restructurings within the LHC control system.

Another design principle which is consistently followed in the application is so-called dependency injection [7], using the spring framework [8]. The main concept of dependency injection is that collaborators of certain 'clients' (objects that use the collaborators) are injected into the clients by a framework, instead of the clients looking up their collaborators. This allows to inject different collaborators in different situations (contexts), e.g. for development, testing or production.

Testing

One big advantage of the abovementioned dependency injection principle is that the resulting code is nicely decoupled and testable. The reason for this is that e.g. mocked or stubbed collaborators can be injected for testing purposes.

In the case of the chroma application, the same principle is also used to start up an instance of the GUI which uses a self-consistent simulation layer, which allows to try and test the application fully without beam. Similar principles are applied in the meantime also to several other software projects and we are planning to generalize these concepts to make them more easily usable [9].

EXPERIENCE AND OUTLOOK

The chroma app proved to be very reliable and the fit algorithms to be robust. The application is used systematically in every fill to check and trim chroma and tune. Up to now, it never caused problems which would have contributed to unavailability of the LHC. Since there are several other applications (automatic laslett feed-forward application, coupling correction, injection phase) which have to be used while filling the LHC, it will be useful for the future to combine these applications into one.

THE FUTURE: LHC SCHOTTKY

As mentioned in the beginning, the described procedures require 'shaking' the beam with the RF frequency, which is undesirable and even dangerous for high intensity beams. The only device which could potentially derive a direct chroma signal from the particle beam is a schottky monitor. Figure 5 shows a typical FFT spectrum of the schottky monitor from which several beam parameters can be extracted. Efforts in this direction are ongoing and gave first good results recently [4, 5]:

- The tune can already be nicely derived from the signal. In contrast to the BBQ devices, this even works on

bunches which are strongly affected by the transverse damper. The corresponding algorithm is already implemented in the device itself and is therefore running online on the frontend computer and prepared for first tests in an operational environment.

- An algorithm to extract chromaticity was developed offline and shows promising results. As an example, Fig. 6 shows data from a machine development session at injection energy, where the chroma was trimmed deliberately from about 4 units up to about 15 units; the plot compares the chromaticity derived from the schottky monitor and the one derived from RF modulation and shows a very good agreement of the two.

The chroma signal processing is already working very well at injection energy; work is still ongoing to also push the signal quality to a similar level during ramp and flat top. Despite those current limitations, it is planned to implement the chroma algorithm in the device itself still before the end of this year. Integrating these signals then into the chroma application will make it possible to easily compare them, get first operational experience of the signal quality and even use them as source for calculating corrections. Later, this would in principle allow continuous chromaticity measurements throughout the whole cycle and would eliminate (or reduce) the need for dedicated cycles to perform the measurements for the chromaticity feed-forward.

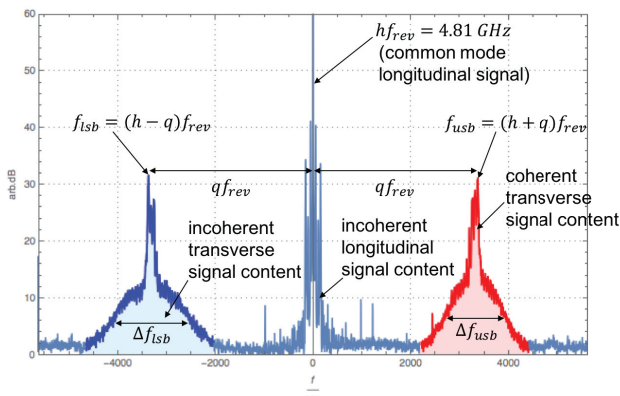


Figure 5: Typical Beam Spectrum as seen by the LHC schottky monitor (Courtesy: M. Wendt, M. Betz).

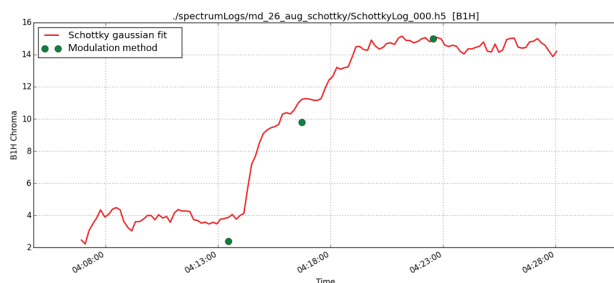


Figure 6: Comparison of chroma derived by the schottky monitor (red line) and chroma as derived with the modulation method (green dots) (Courtesy: M. Wendt, M. Betz).

SUMMARY

The online chroma measurement application turned into a robust tool which was used systematically during filling of the LHC during the first year of LHC Run 2. Next to different measurement algorithms it also allows to calculate corrections and send them directly to the hardware. Planned improvements include better handling of data outliers and integration with tools dealing with other parameters which have to be checked and corrected when filling the LHC.

Particularly promising are the good results from recent tests of the LHC Schottky monitor. The integration of this device into the operational landscape will eventually allow to measure chromaticity and other beam parameters continuously, without shaking the beam with RF modulation. Until then, the RF modulation method will serve as an useful calibration standard during the development of the Schottky data extraction algorithms.

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