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MODELLING AND MEASUREMENTS OF BUNCH PROFILES AT THE LHC

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Abstract

The bunch profiles in the LHC are often observed to be non-Gaussian, both at Flat Bottom (FB) and Flat Top (FT) energies. Especially at FT, an evolution of the tail population in time is observed. In this respect, the Monte-Carlo Software for IBS and Radiation effects (SIRE) is used to track different types of beam distributions. The impact of the distribution shape on the evolution of bunch characteristics is studied. The results are compared with observations from the LHC Run 2 data.

INTRODUCTION

For the LHC luminosity studies, a model including the effects of intrabeam scattering (IBS), synchrotron radiation (SR) and luminosity burn-off is used [1]. The model was constructed based on analytical models which assume Gaussian beam distributions. A comparison of the evolution of the bunch characteristics as predicted by this model with the measured ones revealed an extra (on top of IBS and SR) transverse emittance blow up in the measured data. One of the attempts to explain this blow up concerns the bunch profiles that appear to have non-Gaussian shapes both at flat bottom (FB) and flat top (FT) energies, i.e. 450 GeV and 6.5 TeV respectively. The aim of this study is to quantify the impact of the distribution's shape on the emittance and luminosity evolution, extending the usual approach of employing the analytical formulas for modelling IBS, which are based on 3D Gaussian beam assumptions [2]. For this, the Monte Carlo multiparticle simulation code for IBS and Radiation Effects (SIRE) is being used [3]. The comparison of the code output with analytical formulas has already been studied for the FB [4] and the nominal collision energy (7 TeV) [5]. In this paper, examples of measured bunch profiles at FT are presented for both planes. The evolution of these profiles is compared to the ones calculated by this code. A comparison between the SIRE code, the Bjorken-Mtingwa analytical formalism [2] and experimental data, is presented for the bunch length evolution at the FT energy.

BUNCH PROFILES AT THE FT ENERGY

It has been generally observed that the bunch profiles in the LHC, both at FT and FB energies, appear to have tails that differ from the ones of a normal distribution. In order to describe more accurately the bunch shape, a generalized Gaussian function, called the q-Gaussian [6], can be used. This distribution has a probability density function given by:

$$f(x) = \frac{\sqrt{\beta}}{C_q}\left[1-(1-q)\beta x^2\right]^{\frac{1}{1-q}} . \tag{1}$$

The parameter q describes the weight of the tails. The heavy tail domain corresponds to $1 < q < 3$, in the limit of $q \to 1$ the distribution becomes a normal distribution and when $q < 1$ the tails are lighter compared to the ones of the Gaussian. The normalization factor C_q differs for specific ranges of the q parameter. The parameter β is always a positive number and for a specific q value the probability density function grows with larger β.

An example of a horizontal bunch profile is presented in Fig. 1 in logarithmic scale. Two fitting methods were applied; a Gaussian fit represented by a dashed line and a q-Gaussian fit represented by a solid line. The results of the fits are summarized in Table 1. Since the tails of the distribution are non-negligible, the q-Gaussian approaches the profile much better than the Gaussian function, with a reduction of the RMSE (root mean squared error) by a factor of 2. The measurements were performed with the

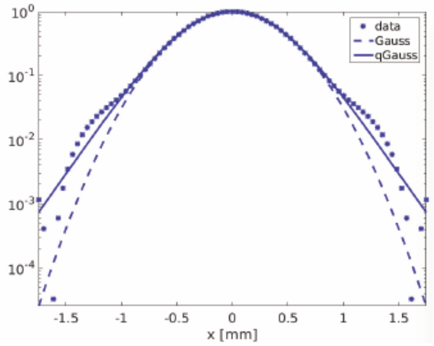

Figure 1: A horizontal bunch profile at the FT energy, as measured by the BSRT, is denoted by blue stars. It is fitted with the Gaussian (dashed line) and the q-Gaussian (solid line) functions.

Table 1: Fit Parameters for a Horizontal Bunch Profile, as Measured by the BSRT, at FT Energy

Hor. Distribution	Fit Parameters
Gaussian (RMSE=0.010)	σ_{rms} = 0.380 ± 0.002 mm
q-Gaussian (RMSE=0.004)	σ_{rms} = 0.403 ± 0.005 mm q = 1.12 ± 0.01

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Beam Synchrotron Radiation Telescope (BSRT) [7] which is a diffraction-limited instrument [8]. Even after using a fast Fourier transform (FFT) filter and a cut at 3 σ, the significant diffraction patterns at the tails of the bunch profiles still persist, implying that with the present instrument, it is difficult to have conclusive estimations of the tails. When $q \neq 1$ the standard deviation of the q-Gaussian fit differs from the Gaussian one and so do the resulted beam sizes (σ_{rms} values in Table 1).

During the energy ramp, the bunches in the LHC are blown up longitudinally in order to avoid instabilities due to the loss of Landau damping [9]. This results in non-Gaussian longitudinal distributions at the start of collisions [10]. The longitudinal distribution is measured by the wall current monitors [11] and the longitudinal synchrotron light monitor (BSRL) [12]. An example of the initial (at the start of collisions) and the final (after 11.5 h) longitudinal bunch profiles [13] are presented in logarithmic scale in Fig. 2. Both profiles are fitted with the Gaussian (dashed line) and the q-Gaussian (solid line) functions. The results of the fits are summarized in Table 2, with the RMSE showing again that the q-Gaussian fit is better than the Gaussian one. As expected from the strong effect of SR at FT, the rms beam size decreases with time. During these 11.5 hours in collisions the q parameter remains smaller than 1. The fact that it slightly increases (around 2%/h) indicates that the distribution becomes slowly Gaussian.

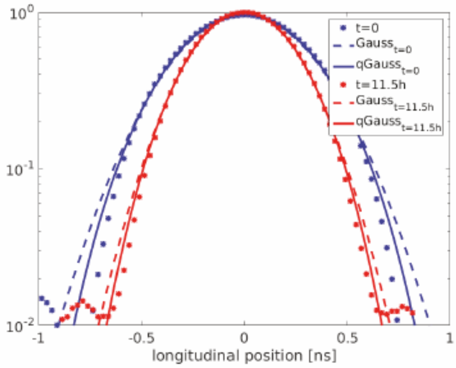

Figure 2: The initial (at the start of collisions) and the final (after 11.5 h) longitudinal bunch profiles, as measured at the LHC, are denoted by blue and red stars respectively. They are fitted with the Gaussian (dashed line) and the q-Gaussian (solid line) functions.

Table 2: Fit Parameters for a Longitudinal Bunch Profile Coming from Experimental Data at FT Energy

Long. Distribution	**Initial Fit Parameters**
Gaussian (RMSE=0.020)	σ_{rms} = 0.299 ± 0.003 ns
q-Gaussian (RMSE=0.011)	σ_{rms} = 0.286 ± 0.004 ns q = 0.88 ± 0.03
Long. Distribution	**Final Fit Parameters**
Gaussian (RMSE=0.013)	σ_{rms} = 0.233 ± 0.002 ns
q-Gaussian (RMSE=0.009)	σ_{rms} = 0.227 ± 0.002 ns q = 0.93 ± 0.03

COMPARISON WITH SIMULATIONS

In the case of non-Gaussian beam distributions no analytical IBS models exist. In order to study the impact of the distribution shape on the emittance and distribution evolution, the Monte-Carlo code SIRE, inspired by MOCAC (MOnte CArlo Code) [14], has been developed [3]. In addition to IBS it also takes into account the effects of synchrotron radiation damping and quantum excitation. After specifying the beam distribution and the optics along a lattice, SIRE iteratively computes intrabeam collisions between pairs of macro-particles. The beam distribution is updated and the rms beam emittances are recomputed, giving finally as output the emittance evolution with time.

The SIRE code accepts any type of distribution as an input. In order to compare the experimental observations with the results of the code, a particle distribution generated from a q-Gaussian function with parameters given in Table 2 was tracked for 11.5 h, taking into account the bunch population decrease with time. The transverse distributions are assumed to be Gaussian since at FT the shape of their tails is not clear due to diffraction. In Fig. 3, the input (t=0) and output (t=11.5 h) distributions, as calculated by the code, are

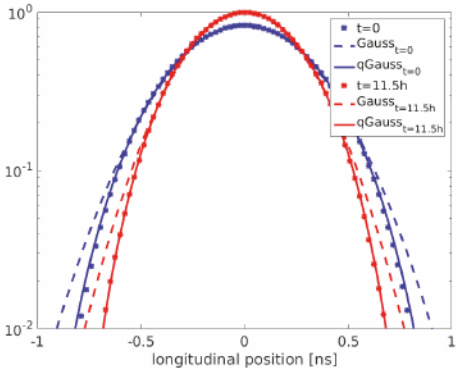

Figure 3: The initial (t = 0) and the final (t = 11.5 h) longitudinal bunch profiles, as calculated by SIRE, are denoted by blue and red stars respectively They are fitted with the Gaussian (dashed line) and the q-Gaussian (solid line) functions.

Table 3: Fit Parameters for a Longitudinal Bunch Profile, as Calculated by SIRE, at FT Energy

Long. Distribution	**Initial Fit Parameters**
Gaussian (RMSE=0.014)	σ_{rms} = 0.307 ± 0.002 ns
q-Gaussian (RMSE=0.003)	σ_{rms} = 0.290 ± 0.001 ns q = 0.85 ± 0.01
Long. Distribution	**Final Fit Parameters**
Gaussian (RMSE=0.014)	σ_{rms} = 0.254 ± 0.002 ns
q-Gaussian (RMSE=0.003)	σ_{rms} = 0.240 ± 0.001 ns q = 0.84 ± 0.01

denoted by blue and red stars, respectively. The fit results for the Gaussian (dashed line) and the q-Gaussian (solid line) functions are presented in Table 3. There is no change at the tails of the tracked distribution, while in reality the profiles become more Gaussian. The q-Gaussian fit shows that within this 11.5 h the rms beam size gets 21% smaller. For the measured bunch profile (in Fig. 2) this reduction is around 26%. This difference can be explained by the fact that in the measurements there is an extra (on top of IBS and SR) transverse emittance blow up the that is not included in the simulations yet.

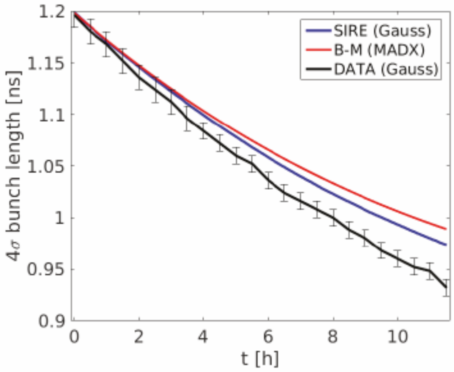

Figure 4: The bunch length (4σ) evolution during several hours in stable beams, as computed by the SIRE code (blue), the B-M analytical formalism (red) and as measured by the longitudinal profile monitors (black) when assuming a Gaussian distribution.

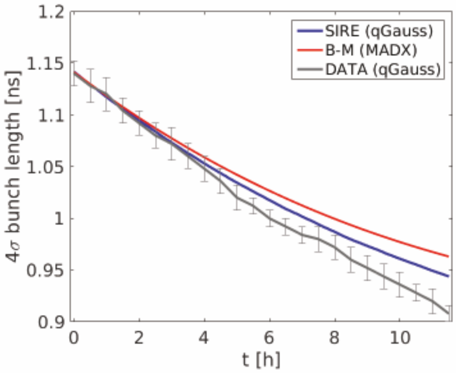

Figure 5: The bunch length (4σ) evolution during several hours in stable beams, as computed by the SIRE code (blue), the B-M analytical formalism (red) and as measured by the longitudinal profile monitors (grey) when assuming a q-Gaussian distribution.

The 4σ-bunch length evolution during several hours in stable beams is shown in Fig. 4 and 5, when assuming Gaussian and q-Gaussian distributions, respectively. The results given by SIRE are denoted by blue lines. The red line corresponds to the evolution calculated by the IBS module of MADX [15], which is based on the analytical formulation of B-M and always assumes Gaussian distributions. The bunch length together with the two standard deviation error-bars, when fitting the data with the Gaussian and the q-Gaussian functions is represented by a black and a grey line, respectively. The initial (at the start of collisions) and final (after 11.5 h) bunch parameters are summarized in Table 4. The $4\ \sigma$ bunch length when assuming Gaussian and q-Gaussian distributions, in the SIRE code and for the fitted data, is denoted by σ_{l_G} and $\sigma_{l_{qG}}$. The bunch length values differ for the two distribution functions used. Generally, for a light tailed distribution the rms value is overestimated by fitting a Gaussian, whereas the opposite is true for a heavy tailed distribution.

Table 4: Initial and Final Bunch Parameters at FT Energy

Parameters	**Initial**	**Final**
Bunch population [10^{11}]	1.05	0.86
ϵ_x, ϵ_y [μm.rad]	3.5, 3.5	2.85, 2.45
σ_{l_G} (DATA, SIRE, B-M) [ns]	1.2	(0.93, 0.97, 0.99)
$\sigma_{l_{qG}}$ (DATA, SIRE, B-M) [ns]	1.14	(0.91, 0.94, 0.97)

In Fig. 4, the divergence between the SIRE and MADX [16] for longer time-spans is probably due to the fact that the two codes make use of different approaches to calculate the IBS effect [1]. The bunch length evolution as calculated by the code is closer to the measured data for the q-Gaussian than for the Gaussian case. In order to make the simulations more realistic the extra transverse emittance blow up should be taken into account in the code.

SUMMARY AND NEXT STEPS

In the LHC, the interplay between a series of effects can lead to non-Gaussian distributions. In this paper, the q-Gaussian function, which is able to describe much more accurately the bunch profiles in the case of non-Gaussian tail populations, is employed. Examples of non-Gaussian bunch profiles at FT were presented. The measured transverse bunch profiles can not be used for conclusive estimations because of the diffraction that affects their tails. However, in the longitudinal plane the tails are clearly underpopulated compared to a normal distribution. For specific bunch parameters, a Gaussian and a q-Gaussian longitudinal distributions tracked for several hours by the SIRE code are compared to the measured profiles from the machine. The bunch length evolution calculated by the code is close to the real data during the first hours at stable beams but start diverging after some hours. This difference can be explained by the extra emittance blow up observed in the transverse plane in the LHC data, while the simulation includes only IBS and radiation effects. The comparison with the analytical model of B-M for Gaussian bunch distributions is also presented. In order to understand the impact on the evolution of the bunch characteristics and finally on the luminosity evolution, various cases of non-Gaussian distributions, also in the transverse plane, are currently being tracked.

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[1] SIRE uses the classical Rutherford cross section which is closer to the Piwinski formalism [17]

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