

MODELLING AND MEASUREMENTS OF BUNCH PROFILES AT THE LHC FLAT BOTTOM

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Abstract

At the LHC flat bottom the interplay between a series of effects (i.e. intrabeam scattering, longitudinal beam manipulations, non-linearities of the machine, etc.) can lead to an increase of the tails' population of the beam distributions, which may become non-Gaussian. This paper presents observations of the evolution of particle distributions in the LHC flat bottom. Novel distribution functions are employed to represent the beam profiles, and used as a guideline for generalising emittance growth rate estimations due to IBS. Finally, an attempt is made to benchmark an IBS Monte-Carlo simulation code, able to track 3D particle distributions, with the measured beam profile evolutions.

INTRODUCTION

One of the dominant effects of the emittance evolution in all parts of the LHC cycle is intrabeam scattering (IBS), being more predominant at flat bottom energy (450 GeV) [1]. The existing analytical formulas for modelling IBS are based on Gaussian beam distributions [2]. In the case of LHC, the interplay between IBS and a series of other effects, including longitudinal beam manipulations, non-linearities of the machine, noise, etc., can enhance the tails of the beam distributions, which may become non-Gaussian. The aim of this study is to understand the impact of the distribution's shape on the emittance evolution both at flat bottom (FB) and flat top (FT) energies (7 TeV). For this, a Monte Carlo multiparticle simulation code for IBS and Radiation Effects, SIRE, is being used [3]. A first attempt on benchmarking SIRE with the analytical IBS formulas for LHC at 7 TeV was presented in [4]. In this paper, a benchmarking of the code at flat bottom energy is undertaken. The validation is made by comparing the IBS growths of the emittance and the energy spread derived from SIRE with those calculated by conventional formalism [2].

BUNCH PROFILES AT LHC FLAT BOTTOM

It has been observed that in many cases, the bunch profiles in the LHC, both at FT and FB energies, appear to have heavier tails than a normal distribution. In order to describe more accurately the bunch shape, a generalized Gaussian function, called the q-Gaussian [5], is used. This

distribution has a probability density function given by:

$$f(x) = \frac{\sqrt{\beta}}{C_q} e_q(-\beta x^2), \quad e_q(x) = [1 + (1 - q)x]^{\frac{1}{1-q}} \quad (1)$$

where q is the parameter that shows the weight of the tails and the larger it is the heavier they are. Actually, it is a generalization of the Gaussian for $q \rightarrow 1$. The C_q is the normalization factor that changes for specific limits of the q parameter. In the heavy tail domain, where $1 < q < 3$, it is written as:

$$C_q = \sqrt{\pi} \Gamma\left(\frac{3-q}{2(q-1)}\right) / \left[\sqrt{q-1} \Gamma\left(\frac{1}{q-1}\right) \right]. \quad (2)$$

The parameter β is always a positive number. For a specific q value, the probability density function grows with larger β .

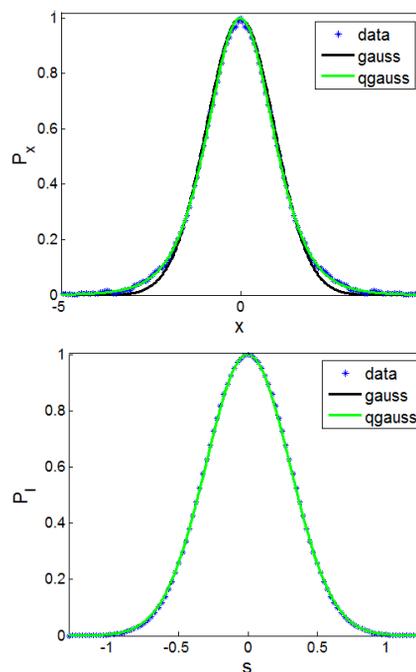


Figure 1: The horizontal (top) and the longitudinal (bottom) beam profiles, at FB energy of the LHC, fitted with a Gaussian black solid line) and a q-Gaussian (green solid line) function.

Figure 1 shows one example of a horizontal (top) and a longitudinal (bottom) bunch profile at FB energy, after cleaning and smoothing the data (blue stars). The vertical beam profile is very similar to the horizontal plane. The data were fitted both with a Gaussian (black solid line) and

a q-Gaussian (green solid line) function. It can be clearly seen that for the horizontal plane, the tails are not negligible and the q-Gaussian function approaches the distribution much better than the Gaussian. On the other hand, in the longitudinal plane it is clearly a normal one ($q \rightarrow 1$). The fit parameters for both cases are summarized in Table 1.

The plots shown here are for profiles taken at specific moments during the FB. Comparing profiles at different time-points, it was noticed that the parameter q of the q-Gaussian fit increases with time. For the example of the longitudinal profile shown here, for 22 min at FB, the q value increases by almost 2%.

Table 1: Example of Fit Parameters for the LHC Bunch Profiles.

Fit Parameters	horiz. profile	longit. profile
Gaussian (μ, σ)	(0, 0.28)	(0, 0.36)
q-Gaussian (q, β, σ)	(1.3, 1.3, 0.27)	(1.0, 10.7, 0.36)

Even though in this paper we will focus only on the FB part of the LHC cycle, it is interesting to notice that after the longitudinal bunch manipulations during the Ramp, the bunch arrives at FT energy with a clearly non-Gaussian shape in the longitudinal plane as well [6].

SIRE BENCHMARKING AT LHC FB

The emittance evolution at LHC FB energy is dominated by the IBS effect, both at the horizontal and longitudinal plane, while no effect is expected in the vertical plane [1]. Several analytical models exist that describe the IBS effect [2, 7], all assuming Gaussian beam distributions, and they are all very well benchmarked with real data for hadron machines [8]. In the case of non-Gaussian beam distributions no theoretical models exist. In order to study the impact of the distribution shape on the emittance evolution and the distribution evolution itself, a code capable of such calculations has been developed, including also Radiation Effects, called SIRE [3]. SIRE was inspired by MOCAC (MONte CARlo Code) [9], a Monte-Carlo code initially used for cooling. After specifying the beam distribution and the optics along a lattice, SIRE iteratively computes intrabeam collisions between pairs of macro-particles. If requested it also evaluates the effects of synchrotron radiation damping and quantum excitation. The beam distribution is updated and the rms beam emittances are recomputed, giving finally as output the emittance evolution in time. A benchmarking of SIRE for the nominal LHC but also variants with lower emittances and at FT energy was presented in [4], showing good agreement.

As mentioned earlier, one of the inputs in SIRE is the file with the optical functions along the ring. As the LHC is a very long accelerator of about 27 km, with a very large number of elements in the sequence (more than 11000), the computational time that SIRE needs to track the distribution for all the elements along the ring is extremely long. In order to reduce the computational time, a study was first

done to identify the optimal minimum number of IBS kick points around the lattice without affecting the overall effect. The IBS growth rates were first calculated for the full optics of the LHC, using the IBS module of the Methodical Accelerator Design code (MADX) [10], which is based on the Bjorken-Mtingwa formalism. Figure 2 shows the IBS growth rates in the longitudinal (green), the horizontal (blue) and the vertical (magenta) plane. The number of IBS kick points around the ring were then gradually decreased, such that the regions where the IBS effect is stronger are always taken into account. For each reduced lattice the emittance evolution was then recalculated for several sets of beam parameters, to assure that the choice of the elements is valid both for regimes that the effect is weak or strong. Finally, the optimal lattice chosen is denoted by red stars (only 24 points) in Fig. 2. Figure 3 shows the hori-

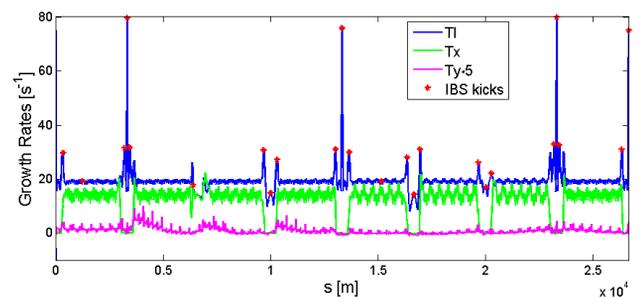


Figure 2: The growth rates in all three planes, along the LHC. The IBS kicks, noted on the longitudinal growth rate with red stars, represent the reduced lattice kicks employed by SIRE.

zonal emittance (top) and bunch length (bottom) evolution due to IBS, normalized to their initial values, during the first 15 min in FB energy. The calculations were again done using the IBS module of MADX. The black solid lines refer to the case of the full lattice while the red dashed ones to the one of the reduced lattice. The agreement is perfect in both planes, allowing the use of the reduced lattice in SIRE.

SIRE has the advantage to accept any type of distribution as an input, defined by the user and can also give as output the distribution state at any stage of the tracking requested by the user. In order to do the benchmarking of

Table 2: Bunch Parameters.

Parameters	case 1
Energy [GeV]	450
$\epsilon_{x,y}$ [$\mu\text{m}\cdot\text{rad}$]	0.8
4σ bunch length [ns]	1.2
Bunch population [10^{11}]	1.6

the code with the analytical formulation of B-M for the LHC FB energy, a Gaussian distribution was firstly tracked for one case of bunch parameters, summarized in Table 2. Figure 4 shows the comparison of the horizontal emittance (top) and energy spread (bottom) evolution after 15 min at

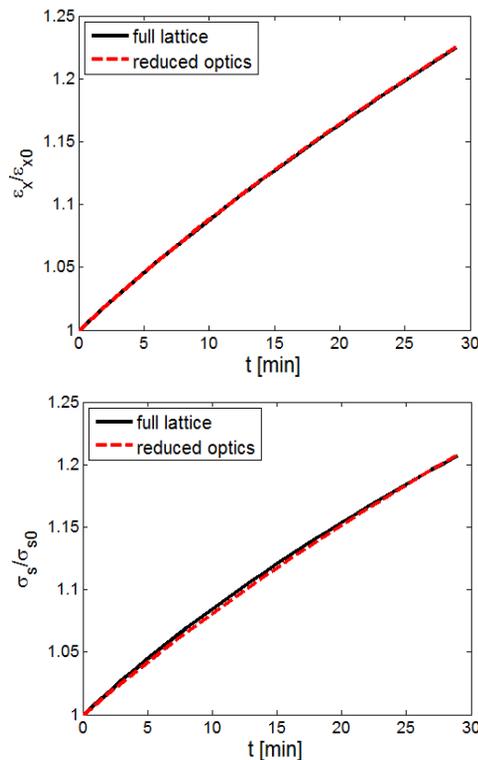


Figure 3: The growth of the horizontal emittance (top) and bunch length (bottom) due to IBS, in a time period of 15 min at FB, when considering the whole lattice (black) solid line) and the reduced lattice (red dashed line), as computed by MADX.

FB, considering the full lattice. The analytical calculations based on the MADX [11] IBS routine are shown in black and the SIRE results are shown in blue. As SIRE uses random number generators for the distributions it calculates, the tracking simulations should be performed several times in order to find the one standard deviation error-bars. Even if not shown in these plots, the spread of the results is quite small.

Even though the SIRE simulation algorithm and the Bjorken-Mtingwa analytical formalism make use of different approaches to calculate the IBS effect (actually SIRE uses the classical Rutherford cross section which is closer to the Piwinski formalism), both estimations agree very well. There is a small difference observed especially for longer time-spans. This is probably due to the fact that SIRE reshapes the beam distributions after each collisional process, while the IBS formalisms assume Gaussian beam distributions throughout the calculations.

It is currently work in progress to track the evolution of the bunch characteristics of non-Gaussian beam distributions and compare with the results obtained for the Gaussian ones.

SUMMARY AND NEXT STEPS

In the LHC, the interplay between a series of effects can lead to non-Gaussian tails. In this paper, a novel distribution function, called the q-Gaussian is employed which has

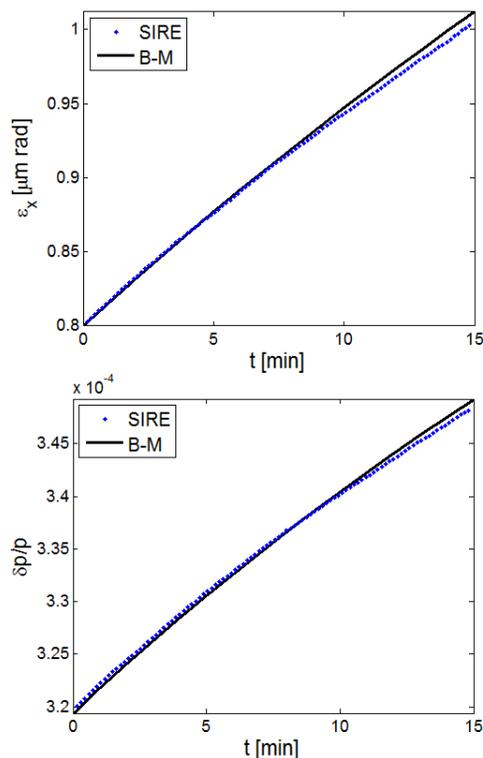


Figure 4: The growth of the horizontal emittance (top) and energy spread (bottom) due to IBS, in a time period of 15 min at FB, computed with SIRE (blue dots) and the Bjorken-Mtingwa analytical formalism (black solid line).

been shown to describe much more accurately the bunch profiles in the case of heavy population.

The multiparticle tracking code SIRE has been benchmarked with the analytical model of B-M for Gaussian bunch distributions. The results of the code's benchmarking with the existing theoretical models, encourages the idea of employing a novel distribution function and then proceed in studying the IBS for various machine parameters including the HL-LHC upgrade. It is currently work in progress the tracking of non-Gaussian beam distributions in order to study the impact of the distribution's shape on the evolution of the bunch characteristics.

At LHC FT energy, the IBS effect becomes weaker while Synchrotron Radiation (SR) damping becomes more pronounced. After the longitudinal beam manipulations during the energy ramp, the longitudinal bunch profiles arrive at FT with a clearly non-Gaussian shape. It is thus very interesting to study the interplay between IBS and SR in this regime, the impact on the evolution of the bunch characteristics and finally to the luminosity evolution.

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