

ELECTRON TRACKING SIMULATIONS IN THE PRESENCE OF THE BEAM AND EXTERNAL FIELDS

M. Patecki, B. Dehning, G. Iadarola, M. Sapinski, CERN, Geneva, Switzerland

Abstract

The ionisation profile monitors installed in the CERN LHC and SPS make use of the ionisation of a small volume of the injected neon gas by the circulating beam. The electrons produced are guided towards the readout system using a combination of electric and magnetic fields. In the presence of the beam field their tracks are modified and the resulting profile is distorted. The Geant4 particle simulation package has been used to simulate the ionisation process, while the CERN developed PyECLLOUD code has been used for tracking of the resulting ionised particles. In this paper the results of simulations are compared with observations and conclusions are presented concerning the accuracy of the reconstruction of high-intensity beam profiles.

INTRODUCTION

The ionization profile monitors [1] operating at the Large Hadron Collider at CERN measure the emittance of the high energy (up to 7 TeV) and high intensity (10^{11} protons per bunch) beams. The circulating beam passing through the vacuum chamber filled with the Neon gas produces electrons by the ionization process. The electrons are guided by an electric and magnetic field towards the anode consisting of a multi channel plate, which amplifies the signal before converting it to light on the phosphor screen. The beam image at the screen is transmitted via an optical system to a CID intensified camera. It is expected that the electrons near to the location of their liberation interact with the electromagnetic field of the circulating beam which affects their trajectories and results in a broadening of the profile. Additionally, as they travel in the presence of the magnetic field, the detection resolution is limited by the gyroradius. The goal of this study is to understand how those phenomena influence the emittance measurements and to provide a correction procedure which ensures the emittance reconstruction with an uncertainty less than 10%.

SIMULATION DESCRIPTION

The PyECLLOUD code [2] is used for the simulation of the beam induced liberation of electrons and the effect of interactions between those electrons and the circulating proton beam (electron cloud). The code was adapted by the authors so that it can be used to determine the electron trajectories in the presence of the proton beam and the external fields.

The input parameters of the simulation (Table 1) define the Gaussian beam. Figure 1 (histogram) shows the simu-

lated profile by tracking the electrons from the beam liberation location to the multi channel plate. The histogram fit result indicates that the profile is not distorted.

Table 1: Simulation Input Parameters

Parameter name	Value
Beam energy	$E_{\text{beam}} = 450 - 7000 \text{ GeV}$
Chamber electric field	$E = \frac{4000\text{V}}{8.5\text{cm}}$
Chamber magnetic field	$B = 0.2 \text{ T}$
Beam intensity	$I = 1.1 - 1.65 \cdot 10^{11} \frac{\text{protons}}{\text{bunch}}$
Horizontal emittance	$\epsilon_x = 1.5, 2.8, 3.5 \mu\text{m}$
Vertical emittance	$\epsilon_y = 1.5, 2.8, 3.5 \mu\text{m}$
Horizontal β function	$\beta_x = 213 \text{ m}$
Vertical β function	$\beta_y = 213 \text{ m}$
Bunch length (4σ)	$\sigma_z = 1.1 - 1.5 \text{ ns}$

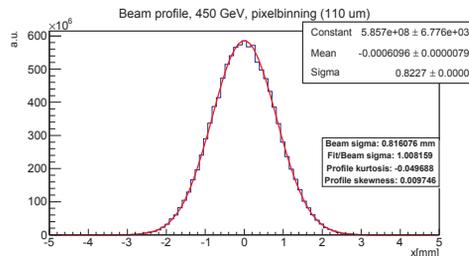


Figure 1: Profile of 450 GeV beam obtained by tracking the liberated electrons (histogram) and a Gaussian fit.

PyECLLOUD code does not include the ionization process: the electrons are randomly (according to the proton distribution of the beam) generated. The Geant4 simulation code is used to obtain the initial electron momentum distribution. The cuts for Geant4 electromagnetic processes were set to 30 eV in order to account for contribution from very low energy processes. Figure 2 shows the momentum distribution in the transverse plane. The momentum in the longitudinal direction is significantly lower but also taken into account. The PyECLLOUD initial momentum of the electrons are generated according to those distributions.

SIMULATION RESULTS

As the output of the simulation beam profiles with a Gaussian-like shape are obtained. A Gaussian fit of the profile, performed using root [3] fitting procedure, is used to determine the profile width expressed as a Gaussian sigma parameter.

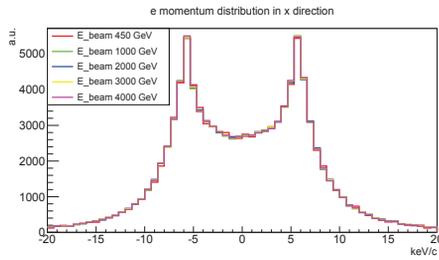


Figure 2: Electron initial momentum distribution in the transverse plane.

The kurtosis test ($K = \frac{1}{n} \sum_{i=1}^n \frac{(x_i - \mu)^4}{\sigma^4} - 3$) is performed to investigate how the profiles differ from the Gaussian shape. Figure 3 shows that the profiles lose their Gaussian shape for some energies. The small values of the kurtosis indicates that a Gaussian parametrisation is appropriate to obtain the profile width. The simulated beam emittance is cal-

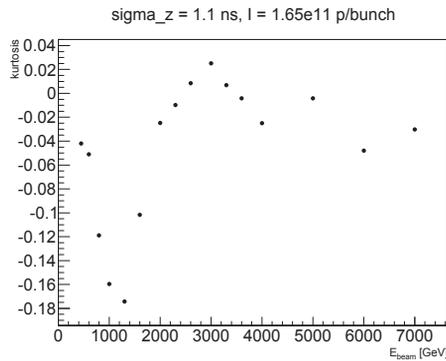


Figure 3: Kurtosis as a function of energy.

culated using the simulated beam σ and Eq. 1 (contribution from dispersion is small and can be neglected):

$$\varepsilon = \frac{\sigma^2 \gamma}{\beta}, \quad (1)$$

where γ is relativistic Lorentz factor and β is the beam optic function.

We assume that the beam emittance is conserved during the energy ramp. By simulating the beams of constant emittance we compare the simulated emittance with an input value. It was checked if the chosen bin width of the histogram affects the profile width. The red points in Figs. 4 and 5 correspond to $1 \mu\text{m}$ bin width. The blue points correspond to the bin size of $110 \mu\text{m}$ which is the CID camera pixel size in the detector. The green points mark the case when the optical PSF ($\sigma_{\text{PSF}} = 25 \mu\text{m}$) is in addition taken into account. Plots show that the results only little depend on the bin width and that the optical PSF is negligible.

Figures 4 and 5 illustrate that the space-charge effects cause the broadening of the beam profile which depends on beam energy and intensity. The discrepancy reaches up to factor 10 for a bunch intensity of $1.65 \cdot 10^{11}$.

ISBN 978-3-95450-122-9

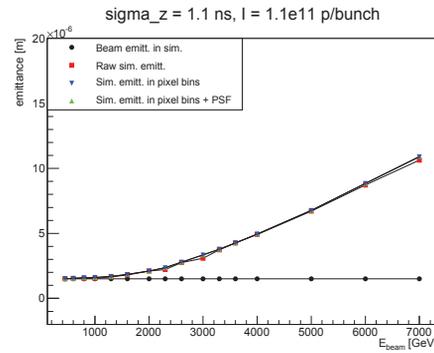


Figure 4: Emittance as a function of energy, for a bunch intensity of $1.1 \cdot 10^{11}$.

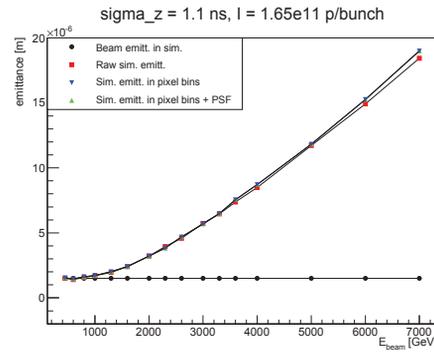


Figure 5: Emittance as a function of energy, for a bunch intensity of $1.65 \cdot 10^{11}$.

CORRECTION PROCEDURE

Two procedures for the emittance correction have been proposed. We assume that the measured Gaussian parametrisation width can be corrected by a quadrature correction, see Eq. 2.

$$\sigma_{\text{meas}}^2 = \sigma_{\text{beam}}^2 + \sigma_{\text{corr}}^2 \quad (2)$$

The σ_{corr}^2 term can be obtained by fitting Eq. 3 to $\sigma_{\text{meas}}^2(E_{\text{beam}})$ dependence.

$$\sigma_{\text{meas}}^2(E_{\text{beam}}) = \frac{A}{E_{\text{beam}}} + \sigma_{\text{corr}}^2, \quad (3)$$

where parameter A is fixed to $\varepsilon \beta E_0$, so $\frac{A}{E_{\text{beam}}} = \sigma_{\text{beam}}^2$ and σ_{corr}^2 is the only free parameter.

The second correction procedure is based on parametrisation shown in Eq. 4.

$$\sigma_{\text{meas}}^2(E_{\text{beam}}) = \frac{A}{E_{\text{beam}}} + B E_{\text{beam}}, \quad (4)$$

where parameter A is the same as in previous case and B is the free parameter.

The comparison of both attempts is shown in Fig. 6. It is easy to notice that the second procedure fits better to the data but it is still not perfect.

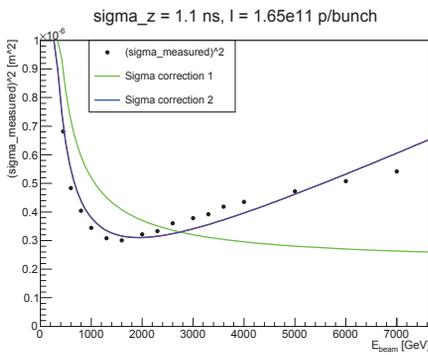


Figure 6: Comparison of two correction methods.

The emittance plots including both correction procedures are shown in Figs. 7 and 8. For the low bunch intensity case (see Fig. 7) the correction is sufficient but for higher intensity (Fig. 8) the correction works worse and requires further development.

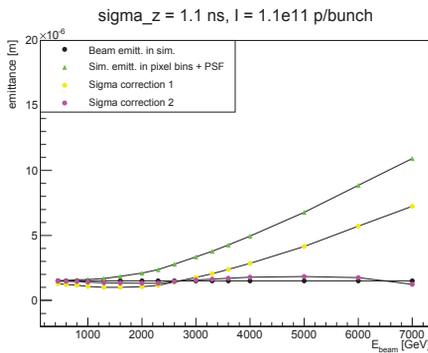


Figure 7: Emittance as a function of energy, for a bunch intensity of $1.1 \cdot 10^{11}$.

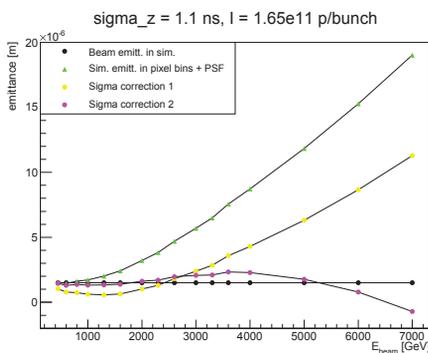


Figure 8: Emittance as a function of energy, for a bunch intensity of $1.65 \cdot 10^{11}$.

E AND B FIELD VARIATION

It was also checked how the increase of the electric or magnetic field in the chamber impacts on the broadening effect. The emittance plot (see Fig. 9) obtained from the

simulations with the chamber electric field of $\frac{10000V}{8.5cm}$ shows that an increase of the electric field does not remove the broadening effect. Increasing the magnetic field from 0.2 T to 1 T shows that the increase of the emittance is largely reduced, see Fig. 10. The results are consistent for any beam considered in LHC, the broadening problem could be solved by increasing the magnetic field to 1 T.

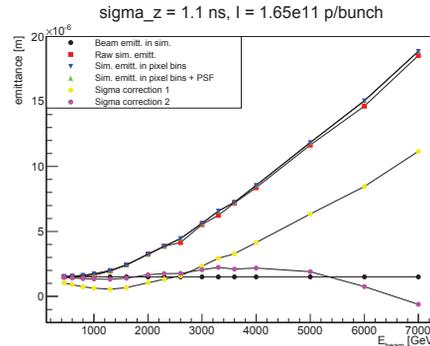


Figure 9: Emittance as a function of energy for $E = \frac{10000V}{8.5cm}$.

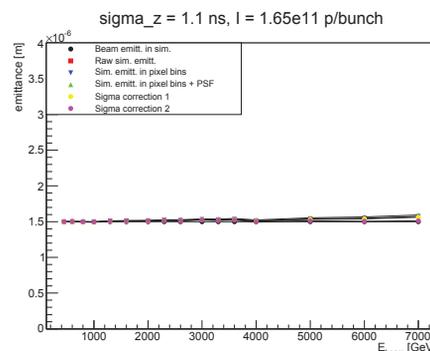


Figure 10: Emittance as a function of energy for $B = 1 T$.

CONCLUSIONS

The PyECLOUD simulation code has been used for electron tracking in the ionization profile monitor in the presence of the beam and external electric and magnetic fields. It was revealed that space-charge effect affects the electron trajectories and cause the broadening of the beam profile.

Two correction procedures have been tested and the one with an energy dependent correction term fits best the observed effects. It was also found that the increase of magnetic field in the IPM to 1 T reduces largely the broadening caused by the beam.

REFERENCES

- [1] M. Sapinski et al., "The first experience with the Beam Gas Ionization Monitor", IBIC 2012.
- [2] G. Iadarola, G. Rumolo "PyECLOUD and build-up simulations at CERN", CERN, Geneva, Switzerland.
- [3] <http://root.cern.ch/>