SIMULATIONS IN SUPPORT OF WIRE BEAM-BEAM COMPENSATION EXPERIMENT AT THE LHC

A. Patapenka*, Northern Illinois University, DeKalb; FNAL, Batavia, IL 60510, USA
Y. Papaphilippou, R. De Maria, CERN, Geneva, Switzerland
A.Valishev, FNAL, Batavia, IL 60510, USA

Abstract

The compensation of long-range beam-beam interaction with current wires is considered as a possible technology for the HL-LHC upgrade project. A demonstration experiment is planned in the present LHC machine starting in 2018. This paper summarizes the tracking studies of long range beam-beam effect compensation in the LHC aimed to aid in planning the demonstration experiment. The impact of wire compensators is demonstrated on the tune footprints, dynamic aperture, beam emittance and beam intensity degradation. The simulations are performed with SIXTRACK code. The symplectic transport map for the wire element, its verification and implementation into the code are also discussed.

INTRODUCTION

The performance of the Large Hadron Collider (LHC) is limited by electromagnetic interactions between proton beams and their surroundings. In particular, one of these effects is the long range beam-beam interaction (LRBBI), which occurs between two beams passing the common beam pipe and when the transverse offset is much larger than the beam sizes. The interaction strength scales as an $1/r$ EM field. The LRBBI can lead to beam emittance growth and beam losses. A straight current carrying wire generates an identical $1/r$ field and it was originally proposed for the LHC to compensate LRBBI effects [1] .

The wire compensators' location should be chosen based on optics considerations [2]. Locality is important, as the long range effects occur in a phase advance of $\pi/2$ from the IP. In this respect, the wires should be located as close as possible to these interactions. Considering that the interactions near the IR are the strongest ones, it was initially thought that the "ideal" positions can be found in lattice locations of equal beta functions (aspect ratio of 1) [3], which can be found +/-104.9 m from IR1 and IR5 and are since marked as BBC (Beam Beam Compensator) in the equipment database. A later study has shown that actually there are fixed aspect ratios depending on the IR layout where the wires can eliminate all excited resonance driving terms excited by the BBLRI [4]. In any case, the BBC locations are in an area where the beams share a common beam pipe, and it is quite difficult to integrate wires, in between them. In this respect, it was proposed [2], that wires are embedded in the jaws of Tertiary Collimators (TCT) in IR5 and IR1, for performing experimental tests in 2017-2018. In this paper we describe the wire model that is implemented into SIXTRACK and tracking studies are undertaken for TCT locations.

* andrei.patapenka@cern.ch

WIRE MODEL

We assume that the wire is a finite straight conductor with infinitely small thickness. Although, a single wire cannot physically exist, we can consider an electric loop as a set of straight wires and there is no objection in the construction of a Hamiltonian and the calculation of a first order symplectic map for each of the elements.

The vector potential of a straight finite thin wire, in Cartesian coordinates, can be described by 4 parameters: the current I, two tilt angles a and b and its length L. Making a natural parametrisation along the wire and using as integration range $(-L/2, +L/2)$, it is possible to obtain, from Biot-Savart law, a generic formula for the vector potential components:

$$A_i(x,y,z) = \frac{I\mu_0 \cos(c_i)}{4\pi}\left[\sinh^{-1}\left(\frac{\frac{L}{2}-a}{\sqrt{b^2-a^2}}\right) + \sinh^{-1}\left(\frac{\frac{L}{2}+a}{\sqrt{b^2-a^2}}\right)\right] . \tag{1}$$

The index i corresponds to x, y or z, c_i to the direction cosines and it could be expressed from the tilt angles, $a = x\cos(c_x) + y\cos(c_y) + z\cos(c_z)$ and $b^2 = x^2 + y^2 + z^2$.

First Order Transport Map

The Hamiltonian parameterized by s (longitudinal coordinate) of single elements that is also used by the SIXTRACK code [5], is represented as :

$$H = -\sqrt{{\beta_0}^2 {p_s}^2 + 2p_s - \left(p_y - a_y\right)^2 - (p_x - a_x)^2 + 1} + p_s - a_s$$

The field (1) of the wire is s-dependent. To take into account the effect of fringe field, an additional parameter must be introduced, the integration length L_{int}. By considering that the integration limits are $[-L_{int}/2, +L_{int}/2]$ assuming the wire parallel to longitudinal axis, and applying the Lie operator, the following equations for the momentum kick, producing by the wire element, can be obtained:

$$\left.\begin{aligned} p_{xn} &= p_x + N_1\frac{x}{R}\left[\sqrt{((L_{int}+L)^2+4R^2)}\right.\\ &\qquad\left.+\sqrt{((L_{int}-L)^2+4R^2)}\right]\\ p_{yn} &= p_y + N_1\frac{y}{R}\left[\sqrt{((L_{int}-L)^2+4R^2)}-\right.\\ &\qquad\left.-\sqrt{((L_{int}+L)^2+4R^2)}\right] \end{aligned}\right\}, \quad (2)$$

with $N_1 = \frac{\mu_0 Ie}{4\pi P_0}$, $R = x^2 + y^2$, L the length of the element, and L_{int} the integration length. For the wire with arbitrary orientation we use the approach described in [6] for constructing symplectic maps of tilted elements. The full first order transport map for the wire element includes the following steps:

- Shift of the space transfer coordinates: $x_n = x - dx$; $y_n = y - dy$; where dy, dx are distances from the wire mid point to the reference orbit;
- Symplectic rotation of coordinate system [6]
- Kick described by (2).
- Backward rotation of coordinate system.

The map has been implemented into SIXTRACK with a slight modification and debugging of a preexisting model [7].

Based on the semi-implicite Euler method, it is possible to construct the first order symplectic integrator [8] for a Hamiltonian system. The first order symplectic integrator for the wire field (1) was implemented into SIXTRACK, as well. The comparison of the first order transport map an the numerical integration has been performed for the nominal LHC parameters without magnet errors. For the test, we used one thousand steps through the wire for the numerical integration. The two models showed almost identical results in turn-by-turn tracking data, for all “physical” case, i.e. when wires are parallel or have a small tilt with respect to the longitudinal axis.

The transport map and numerical integration were also compared as stand alone maps. Different combination of initial coordinates and wire parameters were compared and have shown that differences between the two models can only occur when the particles are crossing the wire plane.

APPLICATION TO THE LHC

The Simulation Procedure

Particle tracking was performed with the SIXTRACK code. Ten thousand macro particle bunch was tracked to calculate beam macro parameters, such as beam intensity and emittance. The initial distribution of particles in the bunch was generated as a multivariate Gaussian function with sigma matrix equals to $T^{-1} \cdot E \cdot T$, where T is one turn Transport Matrix and E is a Matrix of the emittances [9].

The LHC Parameters

The LHC lattice in SIXTRACK input was generated with the following parameters: beam 1 was used as a "probe" beam; the beam intensity was chosen to be $1.2 \cdot 10^{11}$ p/bunch, with nominal 25 ns bunch separation and $\beta^* = 40$ cm; vertical and horizontal emittances were 2.5 μm, beam Energy - 6.5TeV with σ energy spread 1.12^{-4}, the bunch length 75 mm. In accordance with the present LHC parameters, we used the machine geometry with chromaticity 15 units and 550 Amps current in octupoles [10]. No multi-pole errors were included into the simulated sequence.

Compensation Parameters

The wires compensators have to be placed at TCT locations [2]. The optics parameters for the 250 mrad crossing angle at these locations are listed in Tab. 1. The beam-beam interactions, including head-on and LRBBI were switched on only at IP1 and IP5. Number of parasitic collisions per side & per IP was 16 (additional 5 collisions at separation dipole D1 were also included). Switching the wires ON changes the tune of central particle. In order to estimate this effect we performed two sets of simulations - with and without central tune moving back.

Table 1: Optics Parameters at Wire Locations

IP	IP dist[m]	β_x[m]	β_y[m]
IP1	-145.9	2165	758
IP1	172.2	744	1964
IP5	-147.5	2263	910
IP5	150.7	331	1975

Simulations Results

In the present work we focused on such macro parameter as the beam intensity. The beam intensity degradation is the most relevant and observable value, which can be used as a criteria of the efficiency LRBBI effect compensation. Ten thousand particles distributed in 6D Gaussian bunch were simulated, to estimate beam intensity degradation. Ten thousand particles overpopulating the beam tails beyond 3σ were simulated to estimate particle losses from the beam halo. These additional particles were statistically weighted with the bunch core.

The particles distribution was tracked during $1.1 \cdot 10^6$ turns, which corresponds to 97 seconds of the real time. The beam intensity decay τ constant was calculated in assumption, that beam intensity is following the exponential decay $exp(-t \cdot \tau)$. Taking into account, that simulation time range is much more smaller, than the beam life time, we can approximate beam intensity with linear function: $1 - t \cdot \tau$. The resulted beam intensity decay constants for the set of simulations are presented on the fig. 1. Compensation is shown for 8 and 16 beam-beam parasitic collision per IP & per side.

The results on the fig. 1 correspond to the case when central tune remains constant. Simulations predict significant beam life time improvement for 180 mrad crossing angle. Compensation for the case of 220 mrad also shows a decreasing of the decay constant from 0.072 without compensation up to 0.042 when wires are ON. The experimental data was obtained during the MD studies in 2016 by authors of [10].

It should be noted that compensation does not work if the central tune shift (due to the wires impact) is not compensated and becomes closer to 1/3 diagonal line.

Comparison of experimental data from [10] and theoretical results confirms the relevance of the model. Both experiment and simulation predict significant growth of beam losses due to Long Range interactions below 220 mrad. The differences in absolute values can be explained by multipole errors, which were not included into the model.

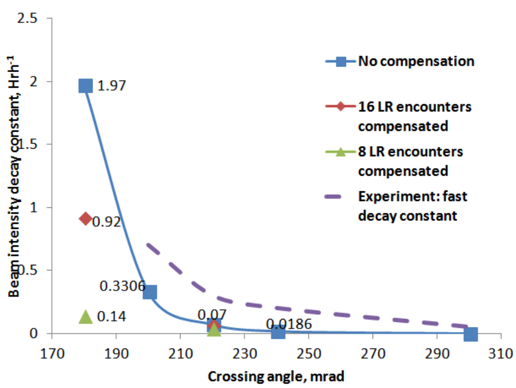

Figure 1: Beam intensity decay constant as a function of time.

The dynamic aperture for the macro-particle bunch remains in range of 2.5-4.0 σ (in transverse plane) for the all simulated cases.

Tune footprints for the case of constant central tune are also visualize the LRBBI compensation, see fig. 2. The footprints are plotted for the Gaussian bunch (transverse amplitude up to 4σ). The color on the figure encodes the order of tune diffusion after five thousand turns.

SUMMARY

A model of a wire element has been developed, verified and implemented into the SIXTRACK code. Beam-beam compensation studies have been initiated under the present LHC conditions with four wire compensators at IP1&5 (2 wires per IP). The results show that the parasitic collision can be indeed compensated, at least in sense of beam life-time improvement. The effect of wire on LRBBI should be investigated further, focusing on parameters such as emittance and bunch and luminosity. For these purposes it's necessary to provide two times better statistic than in the present studies. Some of the future study plans include the improving of the statistic, simulation of more realistic experimental conditions, i.e. bigger emittance for the weak beam and therefore smaller separations in beam sigmas, and studying the compensation of LRBBI at the only one IP. Careful optimization of the experimental conditions is currently under development [11].

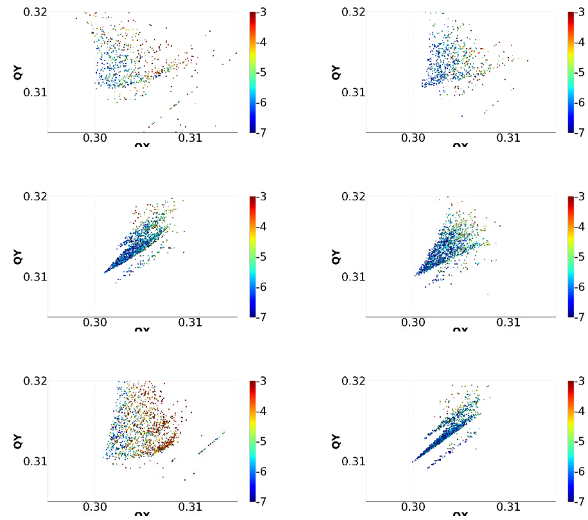

Figure 2: Tune footprints: left column crossing angle 180 mrad; right column crossing angle 220 mrad; from top to bottom: No compensation, 8 parasitic collisions compensated (per IP& per side), 16 parasitic collisions compensated.

ACKNOWLEDGEMENT

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

REFERENCES

[1] P. Koutchouk, LHC Project Note 223, CERN, 2000.

[2] A. Rossi, private communication, CERN, November 2015.

[3] C. Fischer and J.-P. Koutchouk, "Reservations for beam-beam compensators in IR1 and IR5", LHC Engineering Change Order, 2004.

[4] S. Fartoukh, *et.al.,* "Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 12.

[5] *Sixtrack Manual*, CERN/SL/94-56 (AP), Geneva, Switzerland February21, 2014, *http://sixtrack.web.cern.ch/SixTrack/* .

[6] E. Forest, Beam Dynamics: A New Attitude and Framework , Hardwood Academic Publishers, 1998.

[7] B. Erdelyi and T. Sen, "Compensation of beam-beam effects in the Tevatron with wires", FERMILAB-TM-2268-AD, 2004.

[8] V. I. Arnold, Mathematical methods of classical mechanics, Springer-Verlag, New York, 1989.

[9] V.Lebedev and S Bogacz, "Betatron motion with coupling of horizontal and vertical degree of freedom," FERMILAB-PUB-10-383-AD.

[10] T. Pieloni BBLR studies and possible reduction of the crossing angle: machine results, August 2016, `https://indico.`

[11] Y. Papaphilippou, et al., "MD plans for the experimental verification of Beam-Beam long range wire compensation in the LHC", presentation at the LHC Machine Committee, March 2016,