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Large scale beam-beam simulations for the CERN LHC using distributed computing resources

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We report on a large scale simulation of beam-beam effects for the CERN Large Hadron Collider (LHC). The stability of particles which experience head-on and long-range beam-beam effects was investigated for different optical configurations and machine imperfections. To cover the interesting parameter space required computing resources not available at CERN. The necessary resources were available in the LHC@home project, based on the BOINC platform. At present, this project makes more than 60000 hosts available for distributed computing. We shall discuss our experience using this system during a simulation campaign of more than six months and describe the tools and procedures necessary to ensure consistent results. The results from this extended study are presented and future plans are discussed.

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Abstract

We report on a large scale simulation of beam-beam effects for the CERN Large Hadron Collider (LHC). The stability of particles which experience head-on and long-range beam-beam effects was investigated for different optical configurations and machine imperfections. To cover the interesting parameter space required computing resources not available at CERN. The necessary resources were available in the LHC@home project, based on the BOINC platform. At present, this project makes more than 60000 hosts available for distributed computing. We shall discuss our experience using this system during a simulation campaign of more than six months and describe the tools and procedures necessary to ensure consistent results. The results from this extended study are presented and future plans are discussed.

MOTIVATION

In the final design phase of the LHC it is required to verify the long term stability, in particular in the presence of the beam-beam forces which eventually limit the performance of the LHC. An overview of the various aspects was given in [1]. In this study we should like to answer a few questions with impact on the design parameters:

- Which crossing scheme is preferred [1] ?
- What is the effect of triplet errors ?
- Which is the preferred working point ?

Required Computing Resources

For the above, we need to study separately the options with alternating and non-alternating crossing schemes [1]. Errors on the focusing triplet have to be assigned in a statistically significant number and the steps in the tune scan have to be chosen fine enough to not miss bad working points. Beyond these we need to understand the behaviour of so-called PACMAN bunches [1] and to assess the parameter set proposed for the LHC commissioning. For the above study we have estimated about 600000 jobs running about 10 hrs each, corresponding to 6 million CPU hours. This amount of CPU capacity for accelerator design studies is not available at CERN, where development of GRID computing is dedicated to experiment event simulation and processing. The relatively small amount of input/output required, typically less than half a megabyte of input (less than 50 kilobytes when compressed) and a few megabytes of output, make the application rather suitable for grossly parallel distributed computing. Indeed for such massive studies it is necessary to return only the summary output of a few tens of kilobytes.

The CPSS system at CERN [2] which uses the idle time on desktop Windows PCs provides a suitable infrastructure, however with only a few thousand systems available 50% of the time. The CERN IT Department developed the LHC@HOME system [3], based on the Berkeley Open Infrastructure for Network Computing (BOINC) [4], providing access to more than 60000 home computers, donated by more than 30000 volunteers. It is however necessary to run each job at least three times to guarantee the correctness of the results.

SixTrack

The tracking code SixTrack [5] was developed to study the long term stability of the LHC beams in the presence of magnetic non-linearities as well as beam-beam effects [6]. Typically SixTrack simulates 60 particles at a time as they travel around the ring, and runs the simulation for up to 1 million turns. This allows to test whether the beam is going to remain on a stable orbit for a much longer time. Details on the procedure to find the so-called dynamic aperture can be found in [7]. To maximise efficiency, and to provide minimum inconvenience to the LHC@HOME volunteers, SixTrack was modified to incorporate an extremely efficient checkpoint/restart facility.

THE RUN ENVIRONMENT

A set of existing SHELL scripts [8] for submitting work to the CERN LSF Batch System were extensively modified to provide

- Job submission to BOINC and CPSS
- A simple text file database for managing and monitoring the work
- Result retrieval, an essential extension, since the remote jobs have no access to the CERN file systems
- Extensive logging and error checking
- Additional physics options to easily handle multiple amplitudes, tunes, and angles

Running on a Heterogeneous Computing System

An important discovery made with CPSS, and confirmed with LHC@home, is that different Intel and Intel compatible PC processors can return different results, even when a

32-bit static linked absolute binary executable is used. This problem was tracked down to the evaluation of elementary functions such as exponential and logarithm. A solution was found in the elementary function library CRlibm from ENS Lyon [9] which not only provides identical results, but guarantees to provide the correctly rounded double precision results. [1]

THE PHYSICS CASE

While at low energy the main limitation for the beam lifetime comes from the machine non-linearities, i.e. the magnetic field errors, at collision energy the limiting effects are caused by the beam-beam interaction [10]. Due to the large number of bunches, parasitic, so-called long range interactions, are unavoidable and are eventually the limiting factor for the LHC performance.

Crossing Schemes

An active beam-beam compensation scheme is not foreseen for the nominal LHC and the parameters are chosen to minimize the detrimental effects. A passive compensation of the first order effects due to the long range interactions can be accomplished using an alternating crossing scheme [1], i.e. crossing in different planes in the different interaction regions. In particular the tune shift and orbit effects can be compensated very efficiently [1], thus reducing the required operational tune space and avoiding off-centred collisions. In the present layout [11] the long range interactions are important only in the high luminosity (i.e. low β^*) interactions regions. To study their effect on the beam stability we have simulated collisions only in these two interaction points.

PACMAN Effects

An important feature of the LHC is the very different collision pattern of the bunches. This is caused by the non-regular bunch filling and the collision scheme. Only about half of the bunches experience all long range and head-on collisions and are considered as "nominal" bunches. Other bunches have fewer long range (one third of nominal) or head-on (two instead of four) collisions [1]. Some of these effects are compensated by the alternating crossing scheme. These non-nominal bunches are often called PACMAN bunches. Non-alternating schemes (i.e. all crossings in the same plane) may enhance these effects, depending on the distribution of the collision points. It is therefore necessary to investigate the dynamic behaviour separately for these different classes of bunches. In this study we evaluate the dynamic aperture for nominal bunches and separately for the "extreme" PACMAN bunches, i.e. those bunches which experience the least number of beam-beam interactions (head-on as well as long range).

[1]The topic of portability and precision and practical solutions will be covered in a forthcoming paper to be presented at ICAP Chamonix.

Magnetic Field Errors

At injection energy the field errors from the main dipole are the main limit while at collision energy the emittance has decreased and the bad field region of the dipoles is avoided. However, due to the small β^* at the collision point, the beam size becomes large in the final focusing magnets and their field errors need to be considered [11].

PROCEDURE

Parameter set Since the stability further depends on the relative horizontal and vertical amplitudes, different angles in the x-y plane are tested. In this study we expect an important effect since the x-y symmetry is broken in some cases, we use angular steps of 5 degrees, i.e. 17 angles in the x-y plane. For each set of amplitude and angle a horizontal and vertical tune is assigned and the particles are tracked through the elements of the machine.

Magnetic field errors The magnetic field errors in the final focusing quadrupoles were set up according to the specifications in [11]. A correction algorithm was applied to minimize their impact, assuming the errors have been measured and are known. Typically 20 different sets (seeds) of the field errors are used for each case.

Scan of working point In order to find the best working points, the particles are tracking for different tune values. The nominal working point of the LHC in collision is 64.31 and 59.32 in the horizontal and vertical planes. For the tune scan the horizontal tune was varied in steps of 0.001. The tune difference of 0.01 between the horizontal and vertical tune was maintained, i.e. the scan was performed parallel to the diagonal in the working diagram.

MAIN RESULTS

The minimum dynamic aperture in units of the beam size σ as a function of the horizontal tune and for different angles in the x-y plane are shown in Figs. 1 and 2. In Fig. 1 we have used an alternating crossing scheme while in Fig. 2 we show the results when the beams cross always in the horizontal plane. The inherent symmetry in the alternating crossing scheme shows a weak dependence on the angle. The largest aperture can be found around the design working point. In the non-alternating case the angular dependence is very strong with a significantly larger aperture in the plane orthogonal to the crossing plane. Considering all angles, the available tune space is however smaller than in the alternating case. A similar behaviour can be observed in Figs. 3 and 4 where we show the results of the tune scan for PACMAN bunches.

SUMMARY

- We have set up an environment for large scale accelerator physics studies.

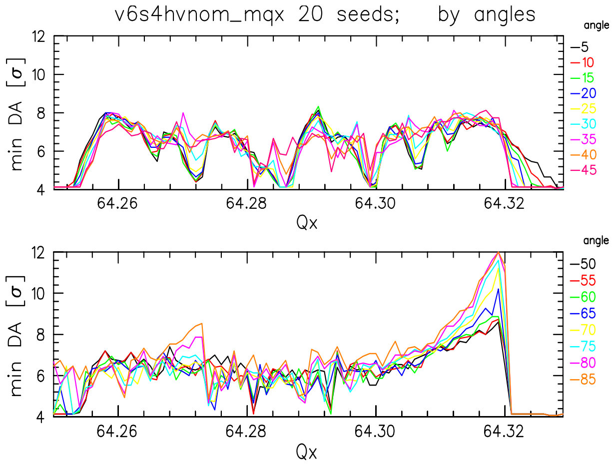

Figure 1: Minimum dynamic aperture for horizontal-vertical crossing

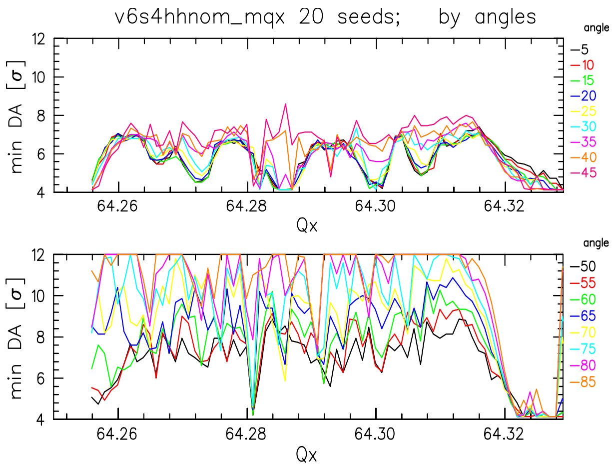

Figure 2: Minimum dynamic aperture for horizontal-horizontal crossing

- The foreseen alternating crossing schemes is superior to a crossing in the same plane.

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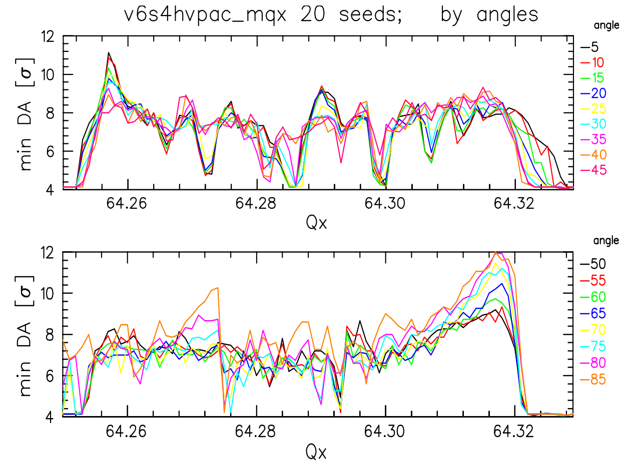

Figure 3: Minimum dynamic aperture for PACMAN bunches for horizontal-vertical crossing

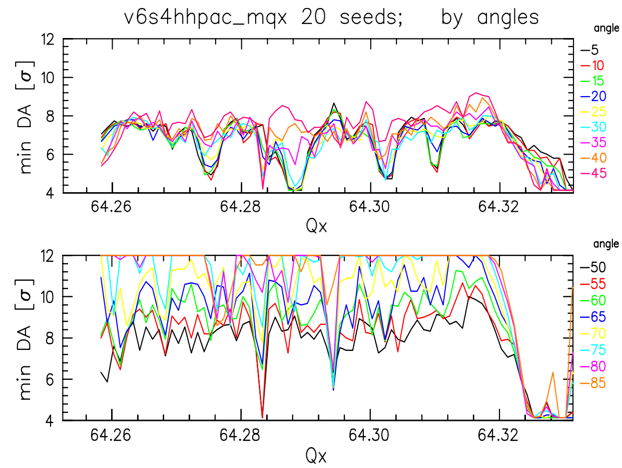

Figure 4: Minimum dynamic aperture for PACMAN bunches for horizontal-horizontal crossing

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