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Request for computation time on parallel machines for the study of beam–beam interactions

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Summary

The control of Beam-Beam Interactions (BBI) in particle colliders is fundamental to preserve beam stability and to achieve the collider maximal luminosity. The Large Hadron Collider (LHC) under construction at CERN has high intensity beams composed of 5616 particle bunches, each containing 10^{11} protons. This represents a considerable computational challenge, requiring the optimization and parallelization of the algorithms. In the context of the PhD work at EPFL of T. Pieloni, we are now developing a new algorithm for the study of BBI effects. The program, called COherent Multi Bunch Interaction (COMBI), is the first attempt of a multi-bunches approach and by its nature should efficiently run on parallel machines. Hence we request to have access to Mizar for an initial phase of 6 months to optimize and test the scalability of the code with few bunches per beam. After the assessment we wish to have 6 months of production on the BlueGene machine for runs with thousands of bunches per beam and multiple interactions.

1 Introduction: the beam-beam interactions

BBI has been the subject of many studies since the introduction of the first particle colliders for high energy physics research. A particle beam is a collection of a large number of charges and represents an electromagnetic potential for other charges, therefore exerting forces on itself and other beams. In the case of particle colliders like the LHC these forces are experienced as localized periodic distortions when the two beams cross each other in the experimental areas (at LHC this corresponds to the location of the ALICE, ATLAS, CMS and LHCb detectors). The forces are most important for high density beams, i.e. high intensity and small beam sizes. The LHC current will be of about 0.5 A per beam, with an energy storage of 720 MJ. The transverse size will be of about 17 μm. These extreme parameters are the key to obtain high "luminosity", i. e. the number of collisions per second needed to study rare phenomena. The BBI is therefore often the limiting factor for the luminosity of colliders, as already observed at the Tevatron (FERMILAB), at RHIC (BNL), at HERA (DESY), and at the SPS (CERN).

2 The BBI simulation code

Although we have a good qualitative understanding of the various phenomena associated to BBI, a complete theory does not exist and exact predictions are still difficult. Numerical

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techniques such as computer simulations have been used with great success to improve the picture on some aspects of the BBI while for other problems the available models have poor predictability.

Some examples of simulation codes developed at CERN for the understanding of BBI effects can be found at URL: http://lhc-beam-beam.web.cern.ch/lhc-beam-beam/, which is the official LHC beam-beam effects team web page. One can find informations on the different effects studied as well as a partial list of the simulation programs developed at CERN in this context.

2.1 The BEAMX code

BEAMX, is an example of a parallel code developed for studying the BBI in the presence of a crossing angle configuration at collision (BEAMX) [1]. The BBI effects were evaluated for beams colliding with finite crossing angles. To accurately calculate the fields produced by particles in a bunch while crossing the opposing bunch the Hybrid Fast Multiple Method (HFMM) [2] is used, for self consistent field calculations. Moreover, the HFMM algorithm has good performances in terms of CPU time. The authors were interested in single bunch collisions (one bunch against one) including a 3D treatment of the BBI. In BEAMX each bunch was sliced into N pieces and each slice was treated independently. To extend the simulations from 2D to 3D a parallel algorithm was implemented for the slices treatment. The algorithm was developed using the MPI protocol and was used on a Linux cluster at TRIUMF, for developing and testing the code and at the THOR cluster at the University of Alberta Physics Dept. A short description of the program, few examples and two papers on the HFMM field solver and on the parallel computation are available on the web page.

2.2 The COMBI code

The program we are now developing is called COherent Multi Bunch Interaction (COMBI) and is the first attempt to have a multi-bunches approach of the problem [3, 4]. In our case we are interested on different BBI effects: the so called "coherent effects" due to the multi-bunches beam coupled by the non-linear beam-beam force. To simulate the LHC beams we need to simulate the situation in 5616 bunches, each bunch represented by at least 10000 "macro-particles", to approximate the effect of 10^{11} protons/bunch. In our case the time consuming part comes from the large number of bunches processed. The field calculations and tracking time must be done for about 1000 interactions per turn and the evolution must be followed by at least 2^{16} turns. For the field calculations we will use the HFMM method for a correct quantitative treatment as well as a simplified but fast Gaussian approximation. It is found that the cpu time needed is proportional to the number of bunches and in the case of HFMM gets very soon too large for normal computers. For this reason our program structure was developed to allow the treatment of each bunch independently in such a way to be efficiently ported to parallel machines.

More in detail, both LHC beams are made of 2808 bunches each, one beam traveling clockwise and the other beam counter-clockwise, the bunches can meet around the ring at 5616 positions. Since the beams are separated in a large fraction of the machine, only at about 124 positions two bunches of the beams meet and a BBI occurs. Fortunately for a realistic simulation of the expected effects not all bunches need to be simulated. In a first stage we would simulate only 72 bunches. Following the results we will later move to 432, 864 and finally to 2808 bunches. In our simulation each bunch is represented by 10^4 to 10^6 macro-particles, replacing the nominal 10^{11} particles per bunch. These numbers are necessary and sufficient to obtain the required resolution and numerical stability.

Each bunch is described by a data structure of about 1.5 to 2 MByte. Whenever two bunches of the counter-rotating beams meet in a position, the BBI must be evaluated. This requires the calculation of the electromagnetic fields produced by the two bunches (solving of the Poisson equation) from their density distribution. This can be a very time consuming process, depending on the algorithm used. For the above parameters this requires between 0.1 and 1.3 s of CPU time on a P4, 3 GHz, depending on the type of interaction. To minimize the data transfer, we propose to implement it such that all bunches of one beam are resident on a single node while the bunches of the second beam are moved from node to node as the beam propagates around the ring. Since significant BBIs only occurs on a subset of 40 to 124 nodes, the calculation can be done in parallel. A dedicated node would act as a dispatcher to assign the bunches of the second beam to the nodes and defines the actions. Some small amount of data (CMS beam position and r. m. s. beam sizes) are communicated to the dispatcher for further processing.The maximum data transfer between nodes is about 1.5 to 2 MByte, i. e. one bunch plus instructions from the scheduler (less than 10 kByte). The phase space variables of each macro-particle are then subjected to these fields and are modified.

In conclusion we foresee that we would need to run on about 80 CPUs for the initial tests. This number should grow up to 1000 for the final phase.

3 Timing

To estimate the time used in the different parts of the simulation program, we have studied two presently available programs: the COMBI program with several bunches using a Gaussian approximation for the field calculation, and the 2D version of BEAMX where a single collision of two beams with one bunch each is simulated. As previously explained, in BEAMX the Hybrid Fast Multipole Method (HFMM) is used for field calculation. In both cases we have used 10^4 to 10^5 macro-particles representing one bunch.
The time T_f measures the time needed for the field calculation and the time T_x is the time spent for all other computations, i. e. bookkeeping, particle and bunch transfer, computation of bunch properties, printing .... While the field calculations can always be done independently for the colliding pairs of bunches, the computations measured by T_x can in general not be separated and parts have to be done in sequence. For both programs we find $T_x \approx$ 4 to 8 ms per turn. This number scales linearly with the number of macro-particles. The field computation needed for a single beam-beam interaction using the HFMM algorithm about 30 to 33 ms are required per turn. For a realistic simulation 124 of these fields calculations are needed per turn. For an increased number of macro-particles (10^5) this number increases to about 210 ms per turn. These numbers should be considered as rough estimates since no systematic study to obtain a large statistical

sample was performed. However, the relative error should be smaller than 50%. Contrary to other algorithms, the time required by the HFMM is almost independent of the grid size and therefore well suited to study long range interactions where the grid size has to be increased to embrace both beams.
From the numbers above it is clear that in the case of the HFMM solver most of the time is spent in the field calculation. Since this is the part of the program where a parallelization would be applied, we can hope for a big gain in speed when we simulate many bunches and therefore simultaneous, independent beam-beam interactions.

CERN notes and reports are available at http://cdsweb.cern.ch/.

References

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[2] F. Jones and W. Herr; *Parallel computation of beam-beam interactions including longitudinal motion*, CERN-AB-2003-019-ABP (2003).

[3] W. Herr; *Spectra of multiple bunches coupled by head-on and long range beam-beam interactions*, CERN-LHC-Project-Note-356 (2004).

[4] W. Herr and T. Pieloni; *Coherent beam-beam modes in the Large Hadron Collider (LHC) for multiple bunches, different collision schemes and machine symmetries*, Proc. of PAC 2005, Knoxville, Tennessee, USA. - 16-20. 5. 2005, (2005). CERN-LHC-Project-Report-845 (2005).

Curriculum vitae of Tatiana Pieloni

- since July 2004 Ph. D. student at the EPFL (Lausanne) and CERN (Geneva).
- Laurea in Fisica (equivalent to Master degree in Physics), Universita' degli Studi di Milano, Italy, 2004.

Research and Development Areas

- Accelerator physics: since July 2004 Ph. D. Student of the Ecole Polytechnique Federale de Lausanne and CERN. Supervisors at EPFL Prof. A. Wrulich and Prof. A. Bay at CERN Dr. W. Herr. The Ph.D. work concerns the study of coherent beam-beam effects in hadron colliders with multi-bunch beams. The studies consist in extending present models to describe the dynamic behavior in the case of many bunches colliding in multiple interaction points, like in the LHC or B-factories. The models must include other types of beam-beam effects like multiple parasitic interactions in a self-consistent form in order to also explore the Landau damping mechanism behavior in the multi-bunches state. The analytical and numerical approach will be supported by experimental verification whenever possible, however the development of the necessary tools, in particular for numerical studies and data evaluation, is considered an essential part of the thesis.
- Solid state physics: from 2001 to 2004, first as a stagier than as a Technical student at CERN, Geneva. Master degree thesis carried out in the AT department, Magnet Test and Measurements group, Analysis and Studies section. Thesis title "An empirical scaling law for the sextupole and decapole snap-back compensation in the Large Hadron Collider (LHC)" supervisors Prof. L. Rossi and Dr. L. Bottura.

Curricula vitae of non EPFL members

Frederick W. Jones (Senior Analyst at Science Division, TRIUMF, Vancouver)

- B. Sc.(Hons.), Mathematics and Physics, University of British Columbia, 1972.
- Graduate studies, Mathematics, University of British Columbia, 1972-3.

Research and Development Areas (last 5 years)

- Accelerator physics: multi-particle simulations for synchrotrons and storage rings; numerical methods for space charge effects in beams; (TRIUMF-CERN Collaboration) studies of beam-beam effects in the Large Hadron Collider, including development of parallel computational models for large-scale simulation of coherent beam-beam effects; (TRIUMF-CERN Collaboration) studies of beam dynamics in the PS Complex; (EURISOL Design Study) development of a simulation framework for a Beta Beam neutrino facility.

- Computational physics: numerical solution of Laplace and Poisson equations and development of the Relax3d code; application of scripting, GUI and visualization techniques in physics computing.
- Nuclear and particle physics: hadronic processes in an object-oriented simulation toolkit (Geant4) for particle interactions in matter; software testing and web-based diagnostic tools for Geant4.

Dr. Werner Herr (Staff member in the AB-ABP-RLC section at CERN)

- Ph. D in natural science, University Heidelberg, 1985.
- Diploma in Physics, University Heidelberg, 1980.

Research and Development Areas

- Accelerator physics: from 1986 to 1987 fellow, and since 1988 staff member at CERN. Initially contributions to SPS and LEP control system software. Large scale simulations of beam dynamics, in particular multi-particle and collective effects. Leader of the MAD-X software project, a general purpose program for the design and simulation of particle accelerators used at CERN and other laboratories in the world. Lecturer at CERN schools on beam dynamics and computational methods in accelerator physics.
- Particle physics: from 1981 to 1985 scientific employee at University in Heidelberg. Teaching and participation in particle physics experiment at CERN. Substantial contributions to general software for data analysis.