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FAST PARALLEL RING RECOGNITION ALGORITHM IN THE **RICH** DETECTOR OF THE **CBM** EXPERIMENT AT **FAIR**

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Быстрый параллельный алгоритм для реконструкции колец в RICH-детекторе эксперимента CBM

В эксперименте CBM (Compressed Baryonic Matter) на ускорительном комплексе FAIR в Дармштадте планируется проводить исследования по рождению дилептонов в соударениях тяжелых ядер. В эксперименте необходима хорошая идентификация электронов для подавления физического фона. Для этого будут использованы детектор черенковского излучения RICH (Ring Imaging Cherenkov) и детектор переходного излучения TRD (Transition Radiation Detector). Быстрые алгоритмы реконструкции событий очень важны для CBM, так как требуется обрабатывать огромные потоки данных, полученных в соударениях.

В данной работе представлен параллельный алгоритм реконструкции колец в детекторе RICH. Современные процессоры развиваются по пути увеличения количества вычислительных ядер внутри процессора и применения векторных вычислений. Технология SSE позволяет применить векторизацию, а многоядерные процессоры позволяют исследовать многопоточность. Обе возможности были реализованы в алгоритме реконструкции колец. Было достигнуто существенное ускорение алгоритма с 357 до 2,5 мс/событие с учетом проведенной оптимизации алгоритмов.

Работа выполнена в Лаборатории информационных технологий ОИЯИ.

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Fast Parallel Ring Recognition Algorithm in the RICH Detector of the CBM Experiment at FAIR

The Compressed Baryonic Matter (CBM) experiment at the future FAIR facility at Darmstadt will measure dileptons emitted from the hot and dense phase in heavy-ion collisions. In case of an electron measurement, a high purity of identified electrons is required in order to suppress the background. Electron identification in CBM will be performed by a Ring Imaging Cherenkov (RICH) detector and Transition Radiation Detector (TRD). Very fast data reconstruction is extremely important for CBM because of the huge amount of data which has to be handled.

In this contribution, a parallelized ring recognition algorithm is presented. Modern CPUs have two features, which enable parallel programming. First, the SSE technology allows using the SIMD execution model. Second, multicore CPUs enable the use of multithreading. Both features have been implemented in the ring reconstruction of the RICH detector. A considerable speedup factor from 357 to 2.5 ms/event has been achieved including preceding code optimization for Intel Xeon X5550 processors at 2.67 GHz.

The investigation has been performed at the Laboratory of Information Technologies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2011

1. INTRODUCTION

The Compressed Baryonic Matter (CBM) experiment is designed to investigate high-energy nucleus–nucleus collisions at the future international FAIR project [1]. The objective of high-energy heavy-ion collision experiments is to explore the QCD phase diagram. The CBM research program includes the study of particles containing charm quarks (D, J/ψ, and ψ' mesons) and low-mass vector mesons decaying into dilepton pairs (ρ, ω, ϕ mesons).

The experimental task is to identify both hadrons and leptons in a large acceptance and to detect rare probes in a heavy ion environment. The experimental challenge is to select rare events in nucleus–nucleus collisions with charged particle multiplicities of about 1000 per central event at reaction rates of up to 10 MHz. In particular, such measurements require fast event reconstruction algorithms.

2. THE RICH DETECTOR

The RICH detector in CBM will serve for electron identification from lowest momenta up to 10 GeV/c needed for the study of the dielectronic decay channel of low-mass vector mesons and J/ψ [2]. The current design of the RICH detector provides about 21 hits/electron ring, the ring radius of electrons is about 5 cm. As the photodetector can only approximately be placed in the focal plane, rings are typically distorted to ellipses with about 10% difference in the length of major and minor half axes. The dimensions of the sensitive pads for the photodetector are 0.58×0.58 cm. The ring and hit density on the photodetector plane is nonuniform and depends on the position on the photodetector. The inner part which is closer to the beam pipe has the highest ring densities. Figure 1 illustrates a typical event display for a part of the photodetector plane including reconstructed rings.

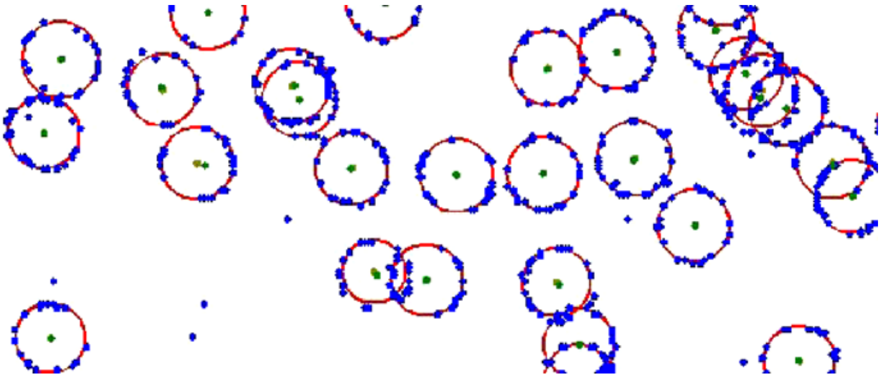

Fig. 1. Part of one typical event in the CBM RICH detector: RICH hits, found RICH rings

3. THE RING RECOGNITION ALGORITHM

The developed ring recognition algorithm is standalone; i.e., the input data is only an array of RICH hits [3]. The algorithm consists of three steps. First, a local search of ring-candidates is performed. It is based on the Hough Transform (HT) method. The second step is a ring selection, in which mainly the quality of rings is determined using an artificial neural network (ANN). The third step is an ellipse fitting of found rings.

3.1. Ring-Candidate Search Based on the Hough Transform Method. HT is a standard method for curve recognition in digital images, e.g., for finding straight lines, circles or ellipses [4]. HT requires very large combinatorics and thus it is an intrinsically slow method. Instead of combining all possible hit triplets in the photodetector plane, we use the fact that the RICH rings have a maximum radius $R_{\max}$ because of the limiting Cherenkov angle. Hit triplets are only combined in a local area of the ring-candidate (see Fig. $2, a$). Hits are collected lying within a predefined region around the initial hit, which defines the preliminary position of the first ring. Then center and radius are calculated using HT equations from every triplet of selected hits and Hough histograms are filled. When the histograms are built, strong peaks in each histogram should correspond to the supposed positions of ring centers (2D histogram, see Fig. $2, b$) and radii (1D histogram). If the peak is higher than a prescribed cut this ring-candidate is accepted and shifted to the ring-candidate array, otherwise rejected.

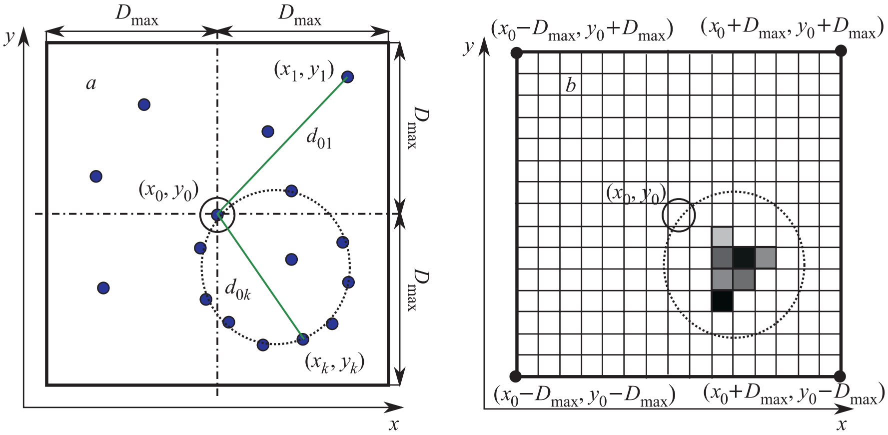

Fig. 2. *a*) Preliminary local hit selection in a region defined by the maximum ring diameter plus a safety margin. *b*) Schematic view of the 2D histogram of ring centers

3.2. Ring Selection. The above-described local ring-candidate search algorithm finds not only correct rings, but also wrong rings as a result of the high ring density in combination with noise hits. A set of ring characteristics had been investigated to be used for a quality estimation of found rings. After a statistical analysis six parameters were selected: the number of hits per ring; the three biggest angles between neighboring hits in the ring; the number of hits in a small corridor around the ring; the position of the ring in the RICH detector; radius; χ^2 of the circle fit. An artificial neural network (ANN) was used for the ring quality calculation. The ANN derives the ring quality using the six input parameters described above. The selection of good rings from the array of found ring-candidates is based on the ring quality which has been calculated by the ANN. With this information, the algorithm compares the ring quality choosing good rings and rejecting repeatedly found rings (clones) and wrongly found rings. The algorithm checks for shared hits with all other ring-candidates. If the ring shares more than 25% of its hits with a better quality ring, it is rejected.

3.3. Ring Fitting. Both circle and ellipse fitting were implemented for the CBM RICH detector. Because of its simplicity and a very high computational speed, circle fitting is used in the ring recognition algorithm. The algorithm which is known as COP (Chernov–Ososkov–Pratt) was implemented [5]. As the rings in the CBM RICH detector have a slight elliptic shape, an ellipse fitting algorithm based on the Taubin method [6] was implemented.

4. SPEEDUP OF THE ALGORITHM

4.1. Algorithm Optimization. As the HT is the most time-consuming part in the algorithm, an optimization of the Hough transform combinatorics is needed. A reduction of the combinatorics was done by dividing hits into several groups and performing the Hough transform for each group independently and then summing up the obtained histograms in one. Other optimization includes: a precise prediction of the local area, mathematic optimization of the algorithm, memory usage optimization in order to store data in cache, removing the best fitted hits of found rings, algorithm parameter optimization, etc.

4.2. SIMD and Multithreading. SIMD is short for Single Instruction Multiple Data. It refers to a computing method that enables processing of multiple data with a single instruction. Requiring fewer instructions to process a given amount of data, SIMD operations yield higher computational speed than scalar operations. The Intel Streaming SIMD Extension (SSE) technology is supported by modern CPUs. Processors with Intel SSE support have a set of 128-bit registers, each of which may contain four 32-bit single-precision floating-point numbers. The best candidate for SIMDization is a computing intensive procedure without branches (if, break, continue), which can work in parallel for multiple data. Multicore processors have made parallel programming more and more mainstream. Motivated by this fact, the possibilities to use multithreading in the ring reconstruction were investigated. For this the Intel Threading Building Blocks (TBB) library was used [7]. TBB is a C++ template library for parallelism. TBB supports scalable parallel programming, which means that programs using TBB will run on systems with a single processor core, as well as on systems with multiple processor cores.

4.3. Hough Transform and SIMD. The first step was to introduce float precision in the HT calculations instead of double precision. It was tested and our results showed that HT works without deterioration with float precision. Then the RICH data were vectorized. This means that each hit vector consists of 4 hit measurements: X_v, Y_v, where $X_v = (X_0, X_1, X_2, X_3)$; $Y_v = (Y_0, Y_1, Y_2, Y_3)$. However, C++ code using SSE instructions uses different expressions compared to code with the corresponding scalar instructions. Rewriting the code using vector instructions would require to provide support for both scalar and vector versions, duplicating modifications, debugging and testing. Therefore, the SSE vector instructions were set in a header file, overloading all operands and inlining several functions. In this way the source code remains the same, and possible changes of the code in the future will be valid for both, scalar and vector, versions. By using the SSE instructions, the calculation of the ring parameters (x, y, r) from 4 triplets at a time using the SIMD execution model was implemented.

4.4. Hough Transform and Multithreading. Multithreading parallelization of the HT algorithm was done on different levels: 1) As the RICH detector consists of two independent photodetectors, the ring reconstruction was done in parallel for each photodetector; 2) the localized HT enables one to use many independent, parallel local ring reconstructions; 3) dividing hits into several groups during the triplet search and performing the HT for each group independently in parallel.

5. RING FINDING RESULTS

In order to test the ring-reconstruction algorithm, central Au+Au collisions at 25 *A*GeV beam energy were simulated with UrQMD [8]. Additional electrons at the primary vertex were embedded in these events in order to estimate their reconstruction efficiency. About 80 rings per event are seen in the RICH detector, mostly from secondary electrons. The comparison of the fast scalar version and the parallel version of the ring finding shows that the momentum integrated reconstruction efficiency is the same for both versions (93%), see Fig. 3. Overall, typically 4% of the approximately 80 found rings are fake rings and 1% clone rings.

A speedup of 74 is achieved by the optimization of the algorithm. By using SIMDization and multithreading, the speed of the algorithm was increased by a factor of 2. In total a speedup factor of 143 was achieved (from 357 to 2.5 ms/event) for the optimized parallel version in comparison to the initial algorithm. The lower than expected speedup factor of 2 for the parallelization is

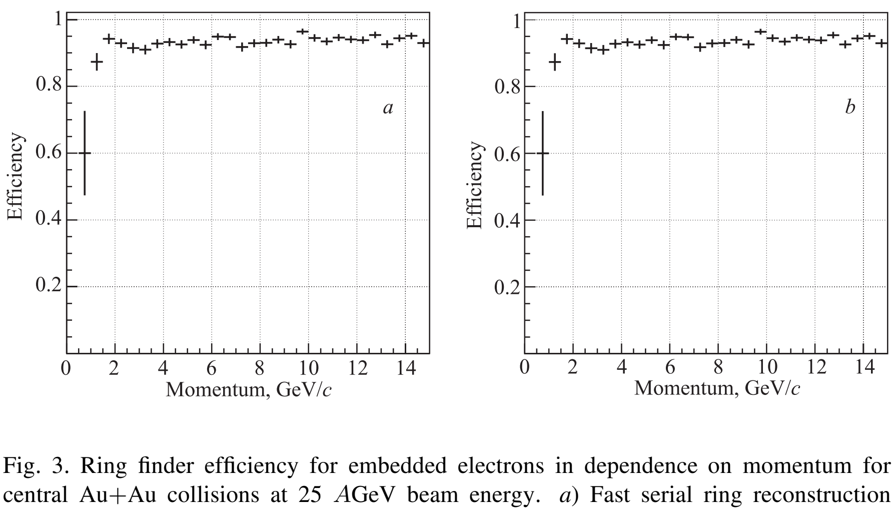

Fig. 3. Ring finder efficiency for embedded electrons in dependence on momentum for central Au+Au collisions at 25 *A*GeV beam energy. *a*) Fast serial ring reconstruction algorithm. *b*) Parallel ring reconstruction algorithm

assumed to stem from the fact that not all parts of the algorithm are parallelized yet and that there is too much time consumption in the synchronization between threads. Further investigations of the parallel ring reconstruction algorithm are ongoing.

6. SUMMARY

Fast event reconstruction algorithms are essential for the CBM experiment. One of the challenges is ring recognition in the RICH detector. A fast and efficient algorithm for ring recognition in the CBM RICH was developed and improved considerably. A parallel version of the algorithm, which uses SIMD and multithreading, was developed. The time for one event reconstruction in RICH (about 80 rings) is 4.8 ms for the optimized scalar version and 2.5 ms for the parallel version. Further investigations of the parallel version are ongoing.

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