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Fast-Timing Tracking Detector for the High-Luminosity LHC

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We propose an innovative detector capable of performing high resolution tracking with ultra-precise time tagging to allow the High Luminosity LHC (HL-LHC) experiments to fully profit from the luminosity upgrade of the accelerator. The increase in the number of visible interactions per bunch crossing will lead to a much larger number of primary vertices and tracks compared to the current LHC conditions, and will inevitably increase tracking inefficiency and ghost track rate. We aim to develop a detector capable of providing 4-dimensional (4D) information, with time resolution in the order of 10 ps and position resolution of about 10 μm, able to operate in a harsh radiation environment exceeding 10^{16} 1-MeV neutrons equivalent per cm^2 and with fast online track triggering capabilities. The precise measurement of the hits time is the key feature to operate an effective pattern recognition that guarantees a high tracking efficiency while enhancing ghost track rejection, and to perform selective track triggering. This detector system will allow to perform precision physics measurements at the HL-LHC operating at instantaneous luminosities almost one order of magnitude larger than the current ones, making efficient use of the whole delivered luminosity.

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1. Introduction

The High-Luminosity LHC (HL-LHC) phase will allow to run the general purpose ATLAS and CMS detectors at an instantaneous luminosity of more than 5×10^{34} cm^{-2}s^{-1} with levelling, allowing to reach an integrated luminosity of 250 fb^{-1} per year. In these conditions the average number of visible interactions per bunch crossing (pile-up) is expected to be more than 140. The LHCb collaboration recently expressed interest in running at the HL-LHC phase at the slightly lower luminosity of 1-2×10^{34} cm^{-2}s^{-1}. Operation of these detectors and in particular precise tracking in such environment will be extremely challenging, especially from the radiation damage and detector occupancy points of view.

Different colliding schemes have been proposed [1] to reduce the line density of pile-up events along the luminous region of the LHC experiments. With the foreseen pile-up density profile, a full-width at half maximum of about 300-600 ps is expected for the primary vertices time distribution, depending on the colliding scheme. A time-tagging resolution in the order of 10 ps will greatly help discriminating overlapping events exploiting time-association of the hits, in order to simplify pattern recognition.

2. A case study: the LHCb experiment

LHCb is investigating the possibility of running at a luminosity of 1-2×10^{34} cm^{-2}s^{-1}, a factor ten higher with respect to the 2019-20 upgrade conditions. Tracking in the forward region, in particular in the vertex detector (VELO) volume, would be very challenging in such environment. A factor of ten increase in track multiplicity is expected, with difficult pattern recognition and a huge increase of ghost track rate. A factor of ten more primary vertices is expected as well, making tracks association to the corresponding vertex much more difficult.

Due to the VELO geometry, a highly non-uniform irradiation of the silicon sensors is expected, with peak values approaching 10^{17} 1-MeV neutrons equivalent per cm^2 in several years of operation. For silicon sensors, the current technology is limited to a few 10^{16} 1-MeV neutrons equivalent per cm^2. In addition, for low p_T physics, the software trigger based on tracking information would demand large computing resources, and huge amounts of data to reconstruct and store is a main issue.

3. Detector concept

We aim at developing an innovative tracking detector with embedded 4-dimensional (4D) tracking capabilities, based on accurate measurements of particles time and position. Real-time track reconstruction with dedicated processors (FPGA) is proposed to allow efficient operation at high luminosity. The precise determination of the time of the track is recognised to be the key feature needed to disentangle many overlapping events and enhance track trigger selection capabilities, as can be seen in Fig. 1. This detector would allow the full exploitation of the physics potential of the HL-LHC experiments.

One of the main challenges for operations at the HL-LHC is that sensors and electronics are required to be able to sustain large hadron fluences, exceeding 10^{16} 1-MeV neutrons equivalent

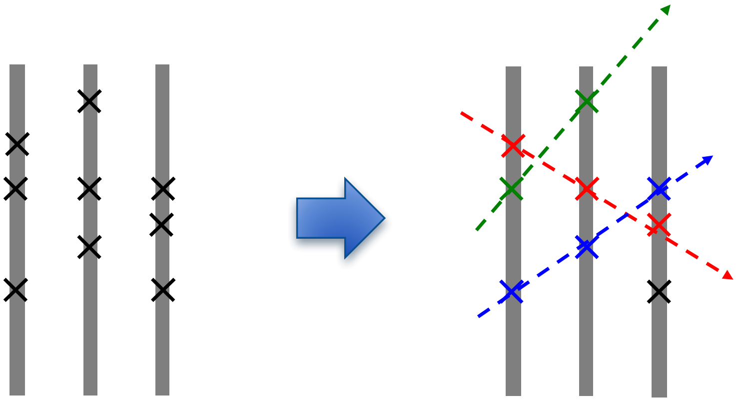

Figure 1: A pattern of hits in different tracking layers (left) could lead to many possibilities for track reconstruction using spatial information only. Adding precise timing information greatly simplifies pattern recognition associating time-compatible hits (right).

per cm^2 . We propose to develop a hybrid pixel detector, that allows to separately optimise sensor and electronics to this purpose. The use of planar and 3D sensors is currently being evaluated with the help of simulations. Our goal is to design a sensor and the front-end electronics capable of providing hit time resolution in the order of 10 ps, together with a hit position resolution in the order of 10 microns.

Crucial aspects to achieve this ultimate time resolution are the optimisation of pixel sensor geometries (for both planar and 3D technologies) to achieve the most uniform electric field, and the design of fast and low noise dedicated front-end ASIC. This front-end will incorporate a fast current amplifier followed by a discriminator and a time-to-digital converter, and will be developed in CMOS technology with fault tolerant architecture which matches the radiation hardness requirements.

4. State of the art

The development of a timing detector with a time resolution of few tens of picoseconds and with a very high channel density is a real challenge. As general guiding lines for timing measurements, the slope-to-noise ratio has to be optimised rather than the signal-to noise ratio alone, which means that the detector must have a very low r.m.s. noise and a very steep signal at the threshold level, as the time resolution depends on the ratio of the two. In addition to that, there are many contributing factors to the final time resolution that must be considered, and which are often conflicting and the best tradeoff must be defined:

- Need of large signals, and fast “signal collection”
- Reduction of input capacitance to the front-end
- Matching of amplifier bandwidth to signal speed

- Electric (weighting) field uniformity for the sensor
- Evaluation of energy release (total, straggling, direction) in the sensor
- Time-walk correction
- Digitization (e.g. TDC bin size and linearity)

State of the art tracking pixel detectors with precise time-tagging is represented by the Gigatracker detector of the NA62 experiment at CERN. This detector features a high channel density (18000 channels per sensor), and is made of a 200 μm thick planar sensor (p-on-n or n-on-p) with 300×300 μm^2 pixels. The sensor is flip-chip bonded to ASICs called TDCpix [2] which have on-pixel amplifier and time-over-threshold discriminator, followed by a time-to-digital converter with 98 ps bin at the chip periphery. The sensors are operated at high over-depletion and measurements show a time resolution of better than 150 ps with minimum ionising particles [3].

A beam test of Ultra-Fast Silicon Detectors (UFSD) recently demonstrated a time resolution of about 30 ps on pad sensors with an area of 1.7 mm^2 [4]. This result is based on the use of 50 μm thick n-on-p Low-Gain Avalanche Detectors (LGAD) with p+ multiplication layer, coupled to a fast amplifier and a 20 GS/s digital oscilloscope. The use of this promising sensor technology for the HL-LHC phase is currently limited by radiation damage, in terms of a decrease in the gain in addition to the signal decrease caused by trapping at fluences beyond 10^{14} 1-MeV neutrons equivalent per cm^2 [5].

5. The 3D sensor option

3D sensors have many interesting features compared to planar sensors and are being proposed as option for the HL-LHC phase [6]. For example, active thickness and collection distance are decoupled, they have a very low depletion voltage so higher electric fields and charge carriers saturation can be reached more easily, the signal development is fast and more concentrated in time, energy fluctuations are collected almost simultaneously, and - most importantly - they are radiation hard. As a drawback, they show larger capacitance and columns are not fully active (however efficiency can be recovered by tilting the sensor).

3D sensors with hexagonal cells have been tested with a fast current amplifier, using a ^{90}Sr source and performing an offline analysis of recorded waveforms [7]. A time resolution ranging from 30 ps (large signals) to 180 ps (small signals) has been measured, limited by the front-end noise. In addition, a sensor made with parallel 3D electrodes from trenches (or “walls”) filled with doped poly-silicon could provide many advantages with respect to the traditional “column” electrodes. For example, null-field regions in the depleted substrate would be reduced to a minimum and, in general, the electric and weighting field would be much more uniform. This has the beneficial effect that the time of the induced signal current pulse would depend mainly on the track traversal time rather than the track location on the pixel cell.

The fast timing properties of 3D sensors have not been fully exploited so far. We plan to use new cell designs optimised for timing (e.g. using trench electrodes), which would allow to achieve a time resolutions in the order of 10-30 ps with careful time walk compensation techniques, such as constant fraction discriminators.

6. Real-time 4D tracking

Feasibility studies of a 4D fast track finding system, using space and time information of the hits, has been recently presented as a possible solution for the low level track trigger of the HL-LHC experiments [8]. The system is based on a massively parallel "artificial retina" algorithm [9] implemented in commercial FPGAs using a pipelined architecture and allows a precise real-time determination of the track parameters (including time) while maintaining a low fraction of reconstructed fake tracks. Track segments ("stubs") can be used instead of hits to improve track pattern recognition in presence of high particle multiplicities. A stub is defined by the spatial coordinates and times of a pair of hits on adjacent sensors, and therefore provides information on the velocity of the particle and its direction, which can be effectively used in the track pattern recognition.

The fast track finding algorithm implemented in FPGA consists of three main blocks:

- switch: delivers in parallel the hits (stubs) from the detectors only to the appropriate cellular units for subsequent analysis;
- engine: block of cellular units for parallel calculation of the retina response, or "weight", for the hits (stubs) in input. Each weight is associated with a track hypothesis and determines how well a set of hits (stubs) is matched with a specific track;
- track fit: interpolation of adjacent cell weights for track parameter determination.

A real-time tracking prototype based on artificial retina algorithm has been recently tested on beam at the CERN SPS with a track rate of about 300 kHz, demonstrating the feasibility of the approach [10]. A device capable of real-time track reconstruction, providing track information with a latency of few microseconds, would improve trigger decisions for the selection of signal events and would reduce the amount of data to transfer, saving bandwidth and resources for data storage. Studies are ongoing to evaluate the performance at high event rates, e.g. at 40 MHz and with hundreds of tracks per event, using latest generation FPGAs and simulated data in input.

Applied to the LHCb physics case, this detector system would allow to perform flavour physics at LHC while operating at instantaneous luminosities more than one order of magnitude larger than the current ones, maintaining large tracking efficiency and negligible ghost track rates. In principle, the proposed solution could be applicable to the ATLAS and CMS physics cases, but its performance must be studied in detail with simulations.

Conclusions

The High Luminosity LHC phase will lead to large delivered instantaneous luminosities to the experiments and, with the currently available detector technologies, chances are high that this luminosity will not be fully usable for physics analysis, due to events pile-up, detector occupancy and reconstruction inefficiencies.

We propose to build an innovative radiation-hard time-tagging pixel tracking detector and a fast real-time track reconstruction system. This detector will use tailored sensors with more uniform field to improve timing response, based on 3D or planar geometry, and a novel front-end read-out based on the radiation resistant CMOS technology.

The proposed 4D detector will enable to exploit the full potential of HL-LHC experiments at CERN, which will be able to continue playing a leading role in the particle physics community in the coming decades.

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