The upgrade of the CMS Tracker for Super-LHC

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Abstract

The CMS experiment at LHC is planning a major upgrade to adapt to increases in luminosity. It will be achieved in two stages, with a long shutdown about ten years after start-up. The new tracker should cope with several hundred interactions per bunch crossing and fluxes of thousands of charged particles emerging from 40MHz collisions. CMS has identified a novel requirement, to utilise tracker data in the first level trigger. The motivations for the upgrade and recent progress are described.

1. Introduction

The LHC peak luminosity of 10^{34} cm^{-2} s^{-1} will eventually deliver about 50 fb^{-1}/yr. CMS was designed for 10 years operation, but only after experiments have run for some time will it be understood whether longer term operation might be possible and worthwhile. Upgrade of the LHC accelerator to Super-LHC foresees operating at 10^{35} cm^{-2} s^{-1} luminosity to provide increased statistics. Under these conditions most of CMS should survive predicted irradiation levels and perform well with few changes. Trigger and data acquisition systems would take advantage of technology evolution to cope with SLHC data volumes and rates.

1.1. Present tracking system

The Tracker surrounds the interaction point and provides precise, efficient measurement of charged particle trajectories and secondary vertices. It comprises pixels in three barrel layers at radii 4.4-10.2 cm and ten barrel layers of silicon microstrips to a radius of 1.1 m. It includes two endcap disks in the pixel detector and nine in the strip tracker on each side, plus inner barrel disks, extending acceptance to $|\eta|$ of 2.5. With about 200 m^2 of active area the CMS

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system is the largest silicon tracker ever built. Its construction required new production and quality control methods. The microstrip detector took cosmic ray data on the surface prior to installation and was inserted inside CMS in December 2007 followed by pixels in July 2008. The pixel system is quickly removable, in case of beam-pipe bake-outs; its installation and connection required only a few days, which is a major advantage for an upgrade. Inner layer replacement was foreseen after several years of high luminosity operation as sensors reach irradiation limits.

2. Upgrades

Most CMS sub-detectors will not change much for SLHC. It is important to maintain compatibility and retain the Level 1 trigger rate limit of 100kHz. Trigger latency can increase from ~3.2μs to 6.4μs, limited by electromagnetic calorimeter pipelines.

The notable exception is the tracking system, whose performance will eventually be degraded by radiation damage caused by immense particle fluxes. Greater radiation tolerance will be required, especially for sensors. In contrast, ASIC electronics should withstand SLHC radiation levels but the 0.25μm CMOS technology pioneered by CMS will be superseded by more advanced processes.

In the congested SLHC environment of 300-400 events per beam crossing, with thousands of particles emerging from interactions, higher granularity is required. CMS also requires to use tracker data in the first level trigger decision.

2.1. Physics requirements

The motivation for a luminosity upgrade is to improve physics studies. Detector performance must remain similar to that at LHC, but with higher particle fluxes, detector occupancies, trigger rates, and radiation damage. Thus, the remarkable achievements in LHC detector development must be surpassed in this even more challenging environment.

Examples of the SLHC physics potential include improvements in Standard Model parameters, e.g. Higgs couplings, and new physics hopefully awaiting discovery, such as SUSY spectroscopy. There will be higher mass searches for composite quarks, new gauge bosons, multi-TeV squarks and gluinos, and extra dimensions.

While a successful search for the Standard Model Higgs might produce a few thousand events, depending on mass, with 300 fb^{-1} of data more events will be needed to confirm its properties and verify its origin. Simulations of HH production predict only a few hundred signal events with significant background even with 3000 fb^{-1} of data.

With such small numbers of events, the detector must be even better than the present one to cope with SLHC particle fluxes and event pileup. If no Higgs exists, deeper investigations of rare channels will be required, also with significant backgrounds. A new detector should adapt to unexpected discoveries.

2.2. Phase I

The first phase of the machine upgrade might be about five years after LHC start-up, to reach a peak luminosity of 2-3x10^{34} cm^{-2} s^{-1}. Inner focusing magnets will be replaced, larger aperture collimators installed and the proton linac replaced to reach the ultimate LHC current. Around the same time the inner layer of the pixel system should be replaced. It looks possible to rebuild the pixel system to achieve improved performance by reducing material.

The new pixel system will have 4 barrel layers at radii from 4-16 cm and 3 disks in both endcaps. The monophase liquid cooling will be replaced by an evaporative CO_2 system with ultra-light mechanics. Data would be transmitted from modules on micro-twisted pair cables to move material on the present bulkhead out of the tracking volume.

The ROC chip would undergo minor changes to increase buffer depths and transmit binary data at 160MHz. The present 40MHz analogue links, which transmit pulse height information and encode digital data, will be modified to send 320Mbps digital data. A new Token Bit Manager chip will multiplex ROC data at 320MHz, and modules to digitise analogue data replaced with deserialisers. These are minor changes to a well proven system which should allow its replacement to be rapidly integrated into CMS.

Although the number of detector modules will roughly double, the system can use the same power cables and needs minor power supply system

changes. The benefit could be a factor 3 reduction in material budget, by weight, of the pixel tracker.

2.3. A better Tracker for Phase II?

High quality tracking and vertexing performance, which at present look excellent, must certainly be maintained in the congested SLHC environment. From simulations of heavy ion events in the present tracker, with similar track density to SLHC, an extra pixel layer would restore track seeding losses. A new layout can be optimised for track finding and jet reconstruction. Granularity must increase because of leakage currents as well as track recognition.

For tracking, multiple scattering, photon conversions, bremsstrahlung and hadronic interactions are undesirable, and depend on limiting material. However cables, cooling and mechanical support grow with power dissipated. A major constraint for a new system is that cooling pipes, power cables and optical fibres follow complex, congested routes and installation was time consuming and difficult. It is unlikely they can be replaced.

2.4. Tracker input to the Level-1 trigger

Single μ, electron and jet Level 1 trigger rates at SLHC will greatly exceed 100kHz and cannot be reduced sufficiently by increasing p_T thresholds. Tracking information in the present High Level Trigger (HLT) provides additional rejection power which motivates future use of Tracker data at L1. One proposal uses cluster width information to eliminate low p_T tracks up to $\eta = 1.7$. An alternative concept deploys closely spaced layers and compares hit patterns. The p_T cut is set by the angle of a track in the layer, and the logic might be relatively simple.

Such methods should improve muon momentum measurements and eliminate fake candidates; a hit in a limited η-ϕ window should discriminate between ambiguous candidates and improve p_T.

In the HLT an energetic calorimeter shower direction is extrapolated to a pixel layer to search for an isolated hit. This could be exploited in the electron trigger but because of high occupancy will not work well at SLHC so alternatives are under study, using coarse pixels at intermediate radius to select high p_T hits which would also be useful for jets.

The major difficulty implementing tracking triggers at Level 1 is that the data volume is too high to transfer all hits off-detector for decision logic. On-detector data reduction is therefore essential. Selective readout, guided by an outer sub-detector, is one possible new feature. It is vital not to degrade performance by introducing more material. Pixellated trigger layers will be more power hungry than microstrip layers, so the challenge is obvious.

2.5. The Phase-II Tracker project

The second phase of the LHC machine upgrade to reach 10^{35} cm^{-2} s^{-1} might be about five years after Phase I. From experience, building a tracker this size requires at least ten years and the trigger requirement makes this even more challenging.

The Phase II design is in progress, by means of simulations guided by a more elementary "layout tool" to quickly evaluate options. Reliability depends on assumptions so it is essential to model power and material accurately, which implies understanding module design and on-detector trigger processing.

Flexible "straw-man" layouts have been built and are starting to produce results for comparisons.

3. Conclusions

CMS is systematically using simulations to define a new Tracker layout and achieve similar performance with reduced material budget. The largest challenges are power and Level 1 triggering.

References

[1] G. Hall, *The upgrade programme of the CMS Tracker at SLHC*. Vertex 2008. To be published in Proc of Science