CMS Tracker Upgrade Issues and Plans: A Short Review

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Abstract The consolidation and upgrade of the LHC accelerators complex is expected to yield a progressive increase in peak luminosity $\mathscr{L}$, exceeding the value of $\mathscr{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (original design figure) after about 5 years of operation, to eventually reach values close to $\mathscr{L} = 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (the so-called Super-LHC). All the experiments will have to make some upgrades to be able to operate at Super-LHC. This article makes a short review of the CMS tracker sub-detector research activities in this direction: we will show the time framework of the evolution plan of LHC, what are the limiting factors of the present-day detector and which requirements come from the luminosity upgrade. We will also describe the main results of the research activities already in place in the field of: sensors, power supply, cooling, layout design and simulations.

Keywords: CMS, LHC, upgrade luminosity, Super-LHC, tracker, sensors, cooling, simulations

1 The LHC upgrade

The Large Hadron Collider (LHC) project just started its operations, with the first beam circulating on September 10, 2008. No collision was achieved yet at the tine of writing of this article, so it is difficult to foresee the outcomes of its first years of life. Nevertheless, it is already possible to sketch the main steps of its future evolution: the nominal luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ will be reached after some upgrades of the machine. These will require about 5 years, during which the accelerator complex will be tuned and the experiments will optimize their performance and collect physics data corresponding to a integrated luminosity of a few hundreds of fb^{-1}.

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If the LHC will then undergo no major upgrade the integrated luminosity delivered to the experiments would be around 1,000 fb^{-1} by 2019 but then it will be difficult to increase significantly the collected statistics in the time framework of this project. For this reason it was proposed a luminosity upgrade in order to further exploit this accelerator [11], with a target figure of $\mathscr{L} = 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to be achieved around 2016–2017 (the so-called Super-LHC, or S-LHC).

The luminosity enhancement is foreseen to be achieved by increasing the number of interactions per bunch crossing, rather than the collision frequency: the commonly accepted upgrade scenario foresees a *decrease* of the bunch crossing frequency (from 40 to 20 MHz), with an increase of a factor 20 in colliding protons per event.

In this scenario, the experiments will have to modify (part of) their detectors to cope with the higher irradiation and particle density, to avoid sensor irradiation damage and signal pile-up.

2 Current CMS tracker

The silicon tracker [1, 2] is the innermost detector of CMS. It extends in the region of pseudo-rapidity[1] $|\eta| < 2.5$, radius $r < 120$ cm, length[2] $|z| < 270$ cm and it is completely based on silicon detectors, covering a surface of $\sim$200 m^2, the largest Si detector ever built. Its aim is to reconstruct the tracks and vertices of charged particles in the highly congested LHC environment.

The present tracker was designed to operate at luminosities up to about $\mathscr{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Significant robustness and redundancy in the tracking capability was implemented in the detector layout, to ensure optimal performance for several years of operation (up to an integrated luminosity of about 500 fb^{-1}), with basically no maintenance/repairs, except for the innermost pixel vertex detector.

The key aspects to solve the tracking pattern recognition problem are a low cell occupancy and a large number of hits per track. To achieve these goals the tracker is structured in two distinct parts: a silicon pixel vertex detector and an outer silicon micro-strip tracker (see Table 1).

The pixel detector is composed of three barrel layers and two end-cap disks per side, and is quickly removable for beam pipe bake-out or replacement.

The Strip Tracker is composed of ten layers of detectors in the barrel region, four of which are double-sided and provide also the z-coordinate measurement. It comprises end-caps made of wedge-shaped detectors matching the types of the corresponding modules in the barrel region (see Fig. 1).

The low occupancy is obtained by using high granularity detectors, and fast primary charge collection, obtained using thin detectors operated with over-depleted

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[1] Pseudo-rapidity η is defined as $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$, with θ polar coordinate in the cylindric reference.

[2] Along the beam direction axis z.

Table 1 Some parameters of LHC and Super-LHC

	LHC	S-LHC
Peak luminosity	$\mathscr{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$\mathscr{L} = 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Integrated luminosity	$100\,\mathrm{fb}^{-1}/\mathrm{year}$	$1\,000\,\mathrm{fb}^{-1}/\mathrm{year}$
C.M. energy	14 TeV	14 TeV
Bunch crossing interval	25 ns	50 ns
# pp events / crossing	~20	~400
# particles in tracker	~1 000	~20 000

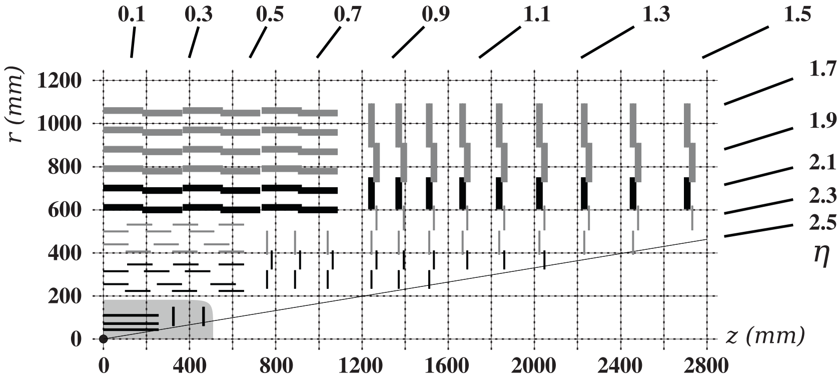

Fig. 1 Schematic view of a quarter of the CMS silicon tracker. The sensor position in the r, z plane is shown here. The inner grayed area is instrumented with pixel sensors. The outer strip tracker is build with single sided (gray) and double sided (black) detectors. Thin lines represent 300 μm-thick sensors, whereas the thick lines represent 500 μm-thick ones

silicon bulks and fast readout electronics. The redundancy is guaranteed by the overall design of the tracker, which allows to measure 10–14 points per track, depending on the pseudo-rapidity.

To reduce the effects of radiation damage and limit the leakage current, the silicon detectors, once irradiated, will be operated at $-10°$C and kept below 0°C also during maintenance.

Results from data collected with the real detector to date [3], during the assembly and commissioning phase, confirm that the detector is operational, with minor (nominal) inefficiencies.

The tracker is characterized by an excellent performance, according to the latest simulations [9], which make use of all the information coming from the construction tests and early data taking:

- Track reconstruction: An excellent track finding efficiency for single muons (details below), with a good fake rejection (high purity)
- Transverse momentum resolution: 0.5% in the barrel region and 3% in the endcap region for tracks with $p_{\mathrm{T}} = 10$–$100\ \mathrm{GeV}/c$
- Tagging and reconstruction of b jets, fundamental requirement for new physics studies ($\mathrm{H} \rightarrow \mathrm{b}\bar{\mathrm{b}}$), for top quark physics and CP violation measurements, is also

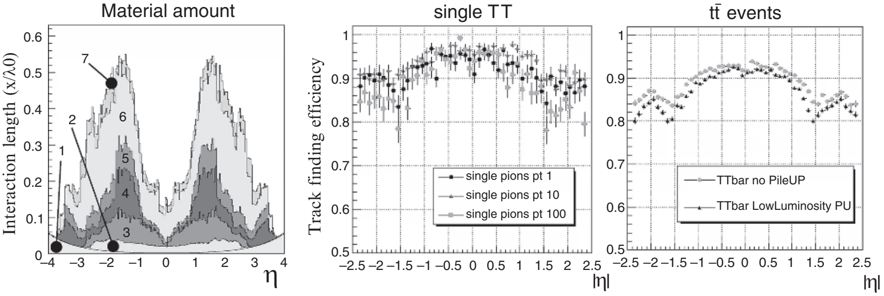

Fig. 2 *Left:* Material amount (in nuclear interaction lengths) break down by function: (1) Beam pipe, (2) Sensors, (3) Electronics, (4) Cables, (5) Cooling, (6) Support, (7) Other. *Center and Right:* Track reconstruction efficiency for single-π and in $t\bar{t}$ events. The drop in efficiency corresponds to material amount peak

based on the good secondary vertex reconstruction: 50–60 μm error in the transverse plane for $p_T = 1\ \text{GeV}/c$, increased to 10 μm for $p_T = 100\ \text{GeV}/c$

This performance is possible mainly because of a highly segmented detector, which both gives the high position resolution and a low occupancy, which is lowest in the pixel vertex detector ($\sim 10^{-4}$) and maximum in the inner layers of the strip tracker (where it reaches 3×10^{-2}).

The large amount of material affects the ultimate performance of the tracker itself (in particular in the momentum resolution at low p_T and the track reconstruction efficiency) as well as electron and photon detectability, and need to be improved in the new tracker design. That can be seen by comparing the track reconstruction efficiency for muons, which is found to be larger than 98% in the whole pseudorapidity range ($|\eta| < 2.5$), with that of pions, which is as low as 80% around $|\eta| \simeq 1.5$. Such behavior is due to the interaction of pions with the material present in the tracker, that peaks in the regions where the reconstruction efficiency is lowest, as shown in Fig. 2.

Although the material breakdown is somewhat arbitrary (as in the case of the ledges supporting the modules, which serve both as cooling contact and as supporting structures), we can see that the material is largely driven by the amount of conductors needed to bring in and out the large current (∼15 kA) required to operate the front-end electronics, and by the need of removing the power dissipated (∼40 kW inside the tracker volume) in a capillary way, to keep all silicon sensors below the temperature limits imposed by the high radiation environment.

3 Tracker upgrade goals and plans

The first upgrade of the LHC to deliver a higher luminosity is foreseen to happen in ∼2013. The following period of running is known as **Upgrade Phase I** and is foreseen to feature a luminosity ramp up to $\sim 2 \times 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$.

The strip tracker is designed in such a way that it will be capable of sustain the increased particle flow, but the Pixel detector will need to be replaced, mainly because of the integrated radiation damage.

Thanks to a specific design requirement, the replacement of the pixel detector is feasible during a winter shutdown. The design and realization of a new detector allows to test new technologies and open the road for the next upgrade.

The "Phase I" Pixel will probably feature: a different pixel size, a fourth barrel layer and a third end-cap disk. It may also feature: a different sensor material (p-type bulk) and pixel size, larger read-out buffers, micro-twisted pair cables instead of Kapton® cables to reduce the amount of material, CO_2 cooling and a fourth barrel layer.

At peak luminosities much higher than $\mathscr{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ also the outer tracker will have to be upgraded, to enhance radiation hardness and granularity. Currently plans are being developed to build a new complete upgraded Tracker around 2018 for the so-called **Upgrade Phase II**.

3.1 Required features for the strip tracker upgrade phase II

For the phase II of the LHC upgrade there is almost no margin of improvement on the ϕ coordinate and momentum measurement precision of the strip tracker, but there are many requirements and constraints in the design. The main ones are mentioned below.

The new detector will have to cope with **higher particle density** ($\sim \times 20$), maintaining the present tracking and vertexing performance. This will certainly lead to a change of the sensor design, with a higher granularity (finer strip pitch, shorter strips), but it will also be possible to allow for a higher channel occupancy (from present $\sim$1% to $\sim$5%), as the present simulations show that an efficient tracking is still achievable with a slightly higher occupancy.

The sensors will have to withstand **higher radiation doses**, thus it is necessary to optimize the choice of sensor material (in details below in section 3.3). The ASICs will profit from new process technologies which were not accessible at the time when the present tracker was designed, with lower power consumption.

An important constraint is that the new tracker will have to **reuse most of the present services** (power cables, cooling pipes, readout and control optical fibers). This means, for example, that the total power supply current is limited and that the bandwidth of each data link must be increased. Such limits can be overcome implementing novel data links and powering schemes (section 3.4).

An additional requirement is the **reduction of the material** inserted in the tracker, in terms of radiation and interaction length, especially in the region around $\eta \simeq 1.5$ (as shown in section 2).

Finally, tracking information must be made available to the **Level-1 trigger**, in order to keep constant the trigger rate without loosing efficiency for physics channels (section 3.2)

While various groups are working to define feasibility and design principles of the components, and different options are proposed, some benchmark simulations are required to compare alternative solutions, keeping in mind that the final layout design will have to be optimized for track finding, reduced material amount and trigger contribution from tracker.

3.2 Design ideas for including tracking information in the trigger

The CMS detector will probably change only its tracking device, with all the other components undergoing only minor improvements/changes. If all the front-end electronics must be kept for the S-LHC upgrade, then the maximum Level-1 trigger rate must be kept to the designed 100 kHz, otherwise one overflows the on-board memory buffers. The problem with this is that the data actually available to the Level-1 trigger do not allow it to reduce the rate down to 100 kHz with the S-LHC parameters, not even by increasing the triggering thresholds on muons and e-γ jets. In Fig. 3 it is reported the foreseen frequency of triggered e-γ jets and muons as a function of the threshold energy and momentum, respectively. The left scale shows the frequencies foreseen for the start-up scenario (LHC nominal $\div$ 5), while the right scale shows the S-LHC scenario (LHC nominal $\times$ 10). It is clear that jet and μ triggers easily saturate the available 100 kHz rate at S-LHC.

If the tracker was able to provide some information to the trigger, this would greatly help in reducing the fake rate, and would allow to keep the rate of accepted events below 100 kHz with a reasonable efficiency.

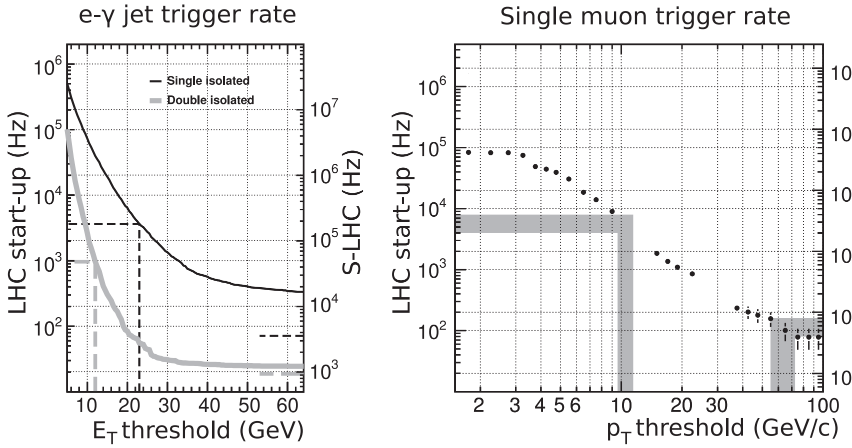

Fig. 3 Level-1 trigger rates as a function of the threshold. Left scale: Low luminosity start-up scenario. Right scale: S-LHC scenario. The marked rates represent the allocated bandwidth for each trigger for the start-up scenario

The tracker trigger information could be used to confirm isolated muons with high transverse momentum and to reduce the fake e/γ candidates by matching the calorimeter signal with inner track/vertex. Moreover the signature of high-p_T particles close to/in jets could help identifying τ- and b-jets.

The approach to this solution is to have *some* information at the Level-1 trigger in order to reduce data volume by applying p_T cuts, as the time constraints (of a few μs) do not allow to perform a complete tracking.

Providing information for the L1 trigger involves sending out data at 20 MHz, and therefore reducing the data volume at the front-end by a large factor (e.g. $\sim$100), to keep the number of links reasonable. Reduction of the data volume must be achieved by rejecting signals from low-momentum particles. Three methods have been proposed so far, none of which is fully proven, but in all cases the idea is to measure the local track angle with respect to the sensor plane to deduce the particle's transverse momentum.

1. Reconstruction of "track stubs" from the correlation of signals in pairs of modules segmented in long pixels. Simulation studies [8] indicate that sufficient rejection of low momentum particles can be achieved with pairs of detectors spaced by $\sim$2 mm placed at a radius of 20–25 cm. High granularity is required, as the method currently relies on the assumption of one hit per readout chip per event, therefore a granularity well below 1%. The approach is in principle applicable also to detectors oriented in the "forward" configuration, by expanding the spacing between the two sensors of the pair by a factor $1/\tan(\theta)(\simeq 5)$.
2. Reconstruction of "track stubs" from the correlation of signals in pairs of strip detectors wire-bonded to the same readout hybrid, which implements correlation functionalities
3. Discrimination on the basis of the cluster size in single sensors [5, 10]. This method has the advantage of not requiring two sensing layers (nor a data link between the two), and therefore it is a priori less demanding in terms of cost, material and power dissipation, but it imposes a constraint in the ratio between pitch and sensor thickness.

For all these methods advantages, disadvantages and feasibility are being evaluated. Also it is of paramount importance to clearly identify the physics requirement for the triggering information, so to avoid a so-called design overkill, which would be not optimal in terms of cost, material amount and thus performance.

3.3 Sensors research & development

The goal of the research on sensors for the strip tracker is to identify one single Silicon sensor type in planar technology for the outer region and one more pixelated (i.e. short strips) for the inner layers.

Studies are being carried out to determine which process is favored for the production for sensors which will have to withstand the intense radiation at the S-LHC:

after half the life of S-LHC (equivalent to 2,500 fb^{-1} delivered integrated luminosity) the expected fluence (Φ) at the inner layer of the strip tracker is $\sim 10^{15}\,\mathrm{cm}^{-2}$ for charged hadrons $\sim 10^{14}\,\mathrm{cm}^{-2}$ for neutrons [7].

The defects created by hadron irradiation cause an increase of the bias voltage needed to completely deplete the sensor and a decrease of the bulk resistance. With the silicon sensors used today and the hadron fluence foreseen at S-LHC, one would expect an increase of the dissipated energy in the sensor bulk, eventually causing a thermal runaway. Studies [6] show that the magnetic Czochralski method allows a much lower bias voltage than the traditional Floating-Zone method for $\Phi > 10^{14}\,\mathrm{n\,cm}^{-2}$.

Another negative effect of sensor irradiation is the loss of Charge Collection Efficiency (CCE) due to the trapping of charge carriers by radiation-induced bulk defects. It was recently shown [4] that n-on-p structures behaves better than p-on-n for $\Phi > 5 \times 10^{14}\,\mathrm{cm}^{-2}$, independently of the crystal production method. A choice of n-on-p has a few drawbacks, namely a higher minimum strip pitch achievable of 50 μm, with respect to 25 μm for the p-on-n, and a larger Lorentz angle. The latter could be compensated by using thinner sensors, which also helps reducing the material amount and the energy dissipation in the bulk.

Innovative readout schemes are under study to cope with the use of shorter strips, which is required to increase the channel granularity. For the inner layers, in order to have the requested granularity, more than two strip segments along the sensors will be needed. This requires special readout techniques like double metal layers or bump bonding.

3.4 Power delivery

A major constraint on upgraded system is the routing of services: all the services to the tracker lying outside the detector volume follow complex congested routes, entangled with other services and with other detectors. Thus it will be impossible to replace external cables and cooling pipes for S-LHC.

The heat load of cables must be removed, and in the present design about 40% of the power is dissipated in external cabling.

$$P_{front-end} \simeq 33\,\mathrm{kW} \qquad P_{cables} \simeq 20\,\mathrm{kW} \qquad I_{cables} \simeq 15\,\mathrm{kA}$$

The foreseen design choices for the upgrade tracker imply an increase of the supply current. Even if the power per readout channel will decrease for the next generation readout chips ($2.7\ \mathrm{mWch} \rightarrow 0.5\ \mathrm{mW/ch}$), the number of channels will increase in order to be compatible with tracking requirements, so the total readout power is expected to be at least in same range as for the present system. Smaller feature size of the front-end chips will result in smaller readout chip supply voltage (1.2 V for the 0.13 μm technology), so larger currents at front-ends will be required. This is not possible without changing the powering scheme, as the external cabling is already at the limit of current it can withstand, and a decrease of a factor x in the front-end voltage at fixed power delivered corresponds to an increase of a factor x^2 in the power dissipated in external cabling.

The proposed solutions up to now involve either DC/DC conversion at the modules or the serial powering of the modules themselves, both techniques would allow to deliver a higher voltage to the front-ends, but neither are proven. The option of powering serially the front-end devices is likely to bring significant complications for very large systems. The technological challenge of DC/DC conversion, instead, consists in developing low-mass, high-efficiency, radiation-hard and magnetic-field tolerant devices, that can be integrated in the front-end without inducing noise in the readout system; different options are being considered, like air-core inductors or switched capacitors.

Also the increased radiation damage plays a role in the power supply scenario: the sensor power will become more important; in order to control it thinner sensors and lower temperatures will be useful.

Reaching lower working temperature, instead, requires a higher cooling power to be delivered with the same external services as the present ones. The most promising solution to this seems to be the two-phase CO_2 cooling, which offers a number of attractive features, like low mass, low viscosity, high latent heat, high heat transfer coefficient, giving in principle the opportunity to realize a system with a smaller number of independent cooling lines and cooling pipes of smaller size compared to the present mono-phase fluorocarbon, possibly coping with higher power dissipation.

3.5 First layout studies and simulation

Some studies on the possible layouts already started: estimates on important parameters like power consumption per channel and expected particle density allow to describe different possible tracker geometries and compare them in terms of foreseen channel occupancy per layer, total power consumption, amount of sensor surface, etc...

It is assumed that a pixel detector with four barrel layers and corresponding end-caps will be placed in the same region as the present-day tracker, so the studies started addressing the outer tracker. The present-day 10-layer configuration is largely redundant; given the material reduction requirement, it will be probably possible to lower the number of barrel layers down to 6. In this case it could be possible also to keep the power consumption in the same range as the present tracker.

Full simulation of possible layouts also already started, these are aimed mainly at validating the tracking with different conditions with respect to the present-day tracker and estimate the potential of trigger information from the tracker. The simulation group is working to develop a set of software tools to assist studies on different layouts, in order to be able to have common benchmarks for comparisons. This is done trying to maximize the overlap of these common software tools with standard CMS Software, which was already extensively validated and can provide a solid framework to study the new features.

4 Conclusions

The LHC upgrade (S-LHC) is foreseen to increase the luminosity of a factor 10 with respect to the nominal LHC. The vertex pixel detector of CMS will have to be replaced 5 years after the start-up (or $\sim$250 fb^{-1}), while whole tracking detector will need a replacement when the major instantaneous luminosity upgrade will be implemented (foreseen about 10 years after the start-up), in order to cope with higher irradiation and higher density of tracks, which will require new radiation-hard sensors and enhanced readout channels density.

If no other sub-detector of CMS will be changed, information from the tracker will be needed at the Level-1 trigger, to keep the rate compatible with the electronics of all the CMS sub-detectors. Thus strategies are being explored to provide some information to the trigger from the tracker.

The requirement to increase the granularity and to create trigger primitives, combined with the need of moderating (and possibly reducing) the material in the tracking volume, constitute a formidable challenge. The task is further complicated by the fact that the new tracker will have to be integrated in the existing CMS detector, with no margin to modify volumes available for detectors and services; in particular, the section of the services going from the tracker external surface to the back-end shall be reused. In order to help achieving such goals while coping with all the constraints, in addition to considering a variety of options in terms of detector layout and readout architecture, innovative powering schemes and cooling technologies are under study.

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