Pixel Group Preparatory Workshop on Future Upgrades: Report from Working Group 3 - "Level 1 Tracking Triggers using the Pixel Detector"

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1 Introduction

This report constitutes a summary of the outcome of the Working Group 3 sessions that took place during the CMS Pixel Group Preparatory Workshop on Future Upgrades.[1] The beginnings of the formulation of requirements asked for in the Workshop Charge is given in this report, as well as a start on an R&D plan. Note that this report comes from the Working Group 3 members, and as such should not be considered to speak for the Pixel Group. This report has been submitted to the Workshop Leaders and the Pixel Group for their consideration.

Members of Working Group 3 are comprised of both members of the Pixel Group and interested collaborators in CMS working on a variety of other projects. This is both natural and desired, given the interdependence of developing an upgraded pixel detector, upgraded tracking detector, and the introduction of an L1 tracking trigger for SLHC. Included in this report is our proposal for the next steps in the establishment of requirements and proceeding with an R&D plan. One of these steps is to join in with the existing CMS SLHC Group and start to participate in the wider discussion within the Tracker Group and with the CMS SLHC Group. This report therefore also serves to inform the Tracker and CMS SLHC Groups of our interest in participating in the work for a CMS upgrade.

1.1 Background

As background, we have included in this section the text from the charge given to the CMS Pixel detector upgrade workshop[2].

The performance of the CMS Pixel Detector will begin to degrade after exposure to a fluence of ~ 6 x 10^{14} particles/cm^2. This fluence will be reached approximately 4-5 years into LHC operation. This is earlier than the end of the first phase of LHC operation, which will achieve an integrated luminosity of more than 300 fb^{-1}. After Phase 1, there will be a long shutdown to upgrade the machine for 10^{35} $cm^{-2}s^{-1}$ peak luminosity, followed by a Phase 2 of several years of running at this higher luminosity. Upgrades to most electronics systems, the trigger, the data acquisition system and some detectors will be required due to higher occupancies and radiation levels, and possibly shorter bunch crossing intervals.

The US Research Program includes funding for R&D to design a replacement pixel detector that can survive and perform well through the end of Phase 1, and another replacement that can survive and perform in Phase 2. It does not include funds to construct either detector. Funds for construction would have to be negotiated separately.

There have been meetings to begin to formulate the R&D for the upgrades of all aspects of the CMS detector to handle 10^{35} $cm^{-2}s^{-1}$ peak luminosity. The Forward Pixel (FPIX) community has participated in these meetings but has not yet developed an R&D plan for either upgrade.

The goal of the workshop was for members of the Forward Pixel Group, along with colleagues in the Barrel Pixel Group, to formulate the requirements of these two upgrades and to outline a program of R&D of a design to meet those requirements.

An important aspect of the workshop was to determine the level of interest in the FPIX and BPIX groups for carrying out this R&D, and to determine whether other collaborators in CMS share this interest. The Silicon Strip Tracker will also carry out an upgrade for Phase 2 (although no intermediate upgrade is currently planned), and may consider pixel detectors for the replacement of the inner layers of the Tracker Inner Barrel. It may make good sense for the “vertex detector” and “tracker” parts of the overall CMS tracking effort to work together to accomplish the upgrades. One goal of the workshop was to prepare the FPIX group to participate effectively in the wider discussion within the Tracker Group.

CMS is considering the addition of a new requirement of the upgraded detectors: to provide track information to the Level 1 (L1) trigger. This is a daunting problem, given the event rates, the amount of data, the high radiation levels, the severe constraints imposed by the existing trigger architecture (short Level 1 latency), and the very limited cable plant. This is a new area of R&D, and is the subject of this section of the report as any L1 tracking trigger is expected to have strong implications for the design of the pixel detectors and the electronics. Moreover, the designs of the total upgraded pixel system, tracker and trigger are inextricably linked at such a deep level that upgrade designs of any of these elements must be closely coupled to the others. It was a major goal of the workshop to begin to establish the requirements for the tracking trigger at L1 and to formulate a plan for meeting them for Phase 2. Also we needed to consider during the workshop the possible incorporation of triggering for the intermediate detector.

Although R&D for a possible upgrade of the pixel detector during Phase 1 running is mentioned in the above charge, it should be mentioned when this upgrade may take place. There will need to be a long shutdown of the LHC to upgrade the LHC with a new beam dump, and to improve the RF and other elements in order to take the luminosity above about 3×10^{33} $cm^{-2}s^{-1}$. This would provide an opportunity to put in or replace a pixel layer of a new design.

An excellent resource of information is the CMS SLHC web site, which includes a link to the draft Expression of Interest[3]. The draft EOI includes an executive summary with a very good overview and outlook for CMS upgrades. The four CMS SLHC workshops held so far provide an excellent source of information on current and past work in almost all areas of CMS SLHC upgrade R&D.

1.2 Goal and Charge for Working Group 3

Working Group 3 was devoted to consideration of an L1 tracking trigger using the pixel detector, and in particular the requirements placed on the pixel detector design by any L1 tracking trigger. The main goals for the workshop for Working Group 3 are listed here:

- Begin developing requirements for Phase 1 and Phase 2 upgrades (e.g. requirements for simulation software)
- Identify technical challenges
- Outline a program of R&D
- Identify areas of expertise for US groups
- Identify groups with strong interest in participation

Another goal that is not included in the list was to prepare members of Working Group 3 so that they could participate effectively in future CMS SLHC workshops.

1.3 Presentations During the Workshop

There were excellent presentations during the Working Group 3 sessions covering a variety of topics. Some of the presentations were in joint sessions with the other two working groups. The list of talks presented at the working group sessions is shown below in chronological order. The slides for these talks can be found at the workshop agenda web page[4].

Wesley Smith	- SLHC Trigger and DAQ
Erik Gottschalk	- Introduction and Charge
Sridhara Dasu	- Current trigger and its limitations
John Jones	- Previous CMS/SLHC tracking trigger studies
Jinyuan Wu	- Track triggering studies for SLHC
Alan Hahn	- Where did trigger primitives in the pixel ROC go?
Xingtao Huang	- Pixel simulation status and tutorial
Vesna Cuplov	- Pixel geometry in the simulation and modifications
Kevin Burkett	- CMSSW tracking software
Jahred Adelman	- CDF tracking trigger
Erik Brubaker	- Ideas for ATLAS tracking trigger
Mike Wang	- BTeV tracking trigger
Meenakshi Narain	- D0 L1 tracking trigger

In addition to the presentations at the working group sessions, there were extensive discussions of a number of topics. In this report we summarize the knowledge gained from these discussions as well as from the presentations.

The outline of the report is given below:

- Describe the SLHC upgrade and time scale, setting the context for this report.
- Describe technical challenges for an L1 tracking trigger.
- Describe what trigger studies have already been done for SLHC.
- List what additional studies are needed for developing an L1 tracking trigger.
- Describe what tools are available, and what needs to be developed. This will form the basis for the "**requirements for simulations**".
- Present **preliminary trigger requirements for Phase 1 and 2**.
- Present a **plan for R&D**, including identifying groups with expertise and groups with interest in working on an L1 tracking trigger.

2 SLHC Upgrade – Setting the context

As described earlier in this document, a replacement pixel detector that can survive and perform well through the end of Phase 1 of LHC operation will likely be needed. Although little else of the detector will change, this may present an opportunity to include components that would make it possible to use pixel data in the CMS L1 trigger, or to demonstrate some pieces of technology needed for Phase 2. After Phase 1, there will be a long shutdown to upgrade the machine for $10^{35}/cm^2$-s peak luminosity. The Phase 2 running at higher luminosity will likely require us to design a replacement pixel detector that can be used for an effective L1 tracking trigger.

Some parameters of the SLHC accelerator upgrade are not yet decided, but are undergoing active deliberation, discussion, and study. It seems that the candidate values for bunch crossing intervals under discussion are 12.5 ns, 25 ns, and 75 ns.

Upgrades of the CMS detector for SLHC are also not yet decided and are also undergoing consideration. Extensive R&D is needed before a decision can be made. However, it is likely that part of the pixel detector will be replaced during Phase 1 operation of the LHC, and for Phase 2, all of the pixel detector and the inner part of the strip detector will be replaced. This gives the physical volume for which upgrades can be made.

The effectiveness of any L1 tracking trigger is inextricably interconnected with the upgrades of many other parts of the CMS detector, including the pixel and strip tracking systems, the front-end readouts and buffering, the L1 trigger components, and depends on the amount of space available and the amount material in an upgraded CMS detector. This means that it is not useful to consider any L1 tracking trigger in isolation, and that the R&D must be closely coupled with R&D involving other areas of CMS upgrades and LHC accelerator upgrades.

To make progress with consideration of requirements for a pixel upgrade for a L1 tracking trigger, we have nevertheless attempted to clearly state the challenges that must be met when considering the constraints as outlined in the CMS SLHC draft EOI. These constraints come from cost considerations in addition to the likely upgrade scenarios of the CMS detector and the LHC accelerator.

The timescale for the R&D was taken to be that given in the CMS SLHC draft EOI and given in Fig. 1. A summary of the proposed roadmap is given below[5].

Within 5 years of LHC start

- New layers within the volume of the current pixel tracker which incorporate some tracking information for an L1 trigger
    - Room within the current envelope for additional layers
    - Possibly replace existing layers
- “Pathfinder” for full tracking trigger
    - Proof of principle, prototype for larger system
- Elements of a new L1 trigger
    - Utilize the new tracking information
    - Correlation between systems

Upgrade to full new tracker system by SLHC (8-10 years from LHC Startup)

- Includes full upgrade to trigger system

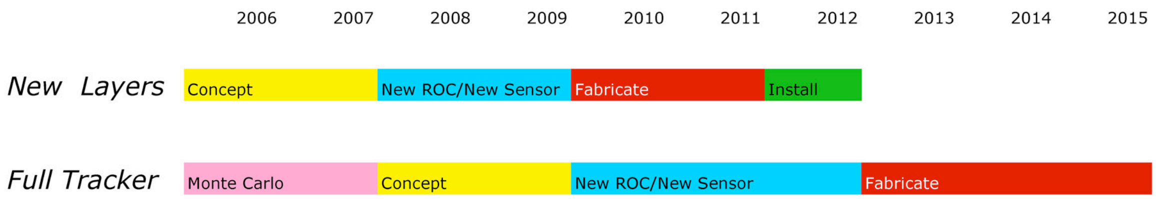

Figure 1. Upgrade time scale as given in the CMS SLHC draft EOI.

3 Technical Challenges for the L1 Trigger

The work presented at the four CMS SLHC workshops and presented in the CMS SLHC EOI shows that CMS must meet a significant number of challenges. One of these is to upgrade the L1 trigger to handle the increased luminosity. This is often illustrated by the single muon rates for various L1 and HLT selections as shown in Fig. 2 for a luminosity of $10^{34}cm^{-2}s^{-1}$, taken from the DAQ TDR which also appears in the CMS SLHC draft EOI[6]. It can be seen that a p_T threshold of about 20 GeV/c is required to keep the rate below 10 KHz, which is 10% of the maximum L1 rate. Even with a linear extrapolation to 10^{35} $cm^{-2}s^{-1}$, too high of a p_T threshold would be required to obtain a reasonable rate. Moreover the curve flattens out, which means that one requires large increases in the p_T threshold to make small reductions in the rate. Effectively the L1 trigger would likely be "broken" at the SLHC.

This motivates the use of tracking information in the SLHC L1 trigger. It appears that tracking information is required at L1 to reduce the L1 rates to acceptable levels. For example the data shown in Fig. 2 show that a reasonable L1 rate is achievable by requiring the presence of a spatially matched track for a high-p_T lepton and use of the track momentum measurement to sharpen the lepton p_T threshold. However, even this minimal requirement introduces significant technological challenges.

It should be pointed out that the data in Fig. 2 uses offline track information to sharpen the muon p_T threshold since the tracking system has ten times the p_T resolution of the muon system. Detailed studies are still needed using a realistic L1 tracking algorithm to check the performance at L1. Also, as was discussed during the workshop, it was not clear that simply requiring a matching track stub/jet and sharpening the p_T threshold is enough for certain trigger channels, for example tau-jets [7], more work on this is required.

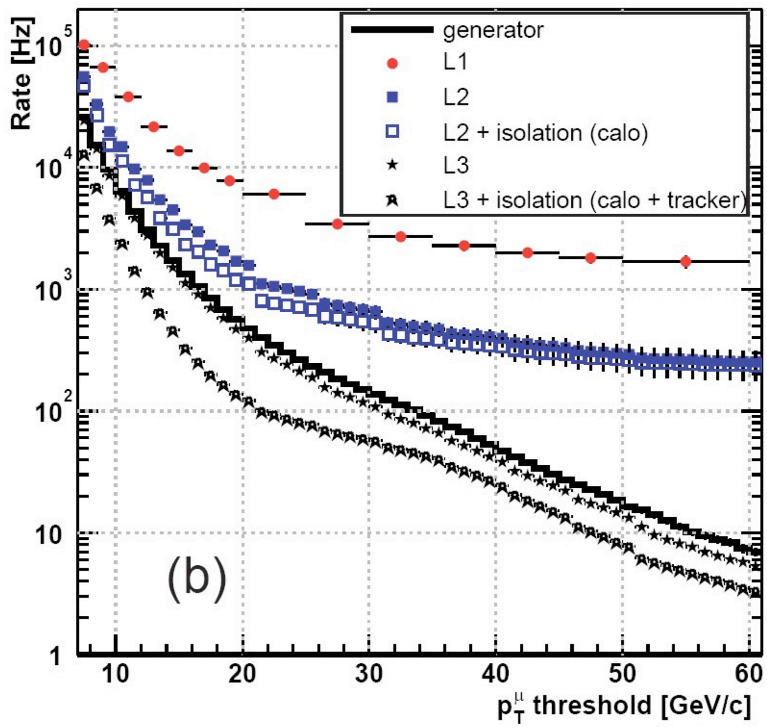

Figure 2. HLT single-muon trigger rates as a function of the p_T threshold for a luminosity of 10^{34} $cm^{-2}s^{-1}$. The rates are shown for L1, L2, and L3, with and without isolation for L2 and L3 (HLT). The rate generated in the simulation is also shown. At L2, using information available at the HLT, a muon must be reconstructed in the muon system and have an valid extrapolation to the collision vertex. At L3 a muon must have more than 5 silicon hits in total in the pixel and strip tracking system[6].

To provide trigger primitives in the CMS L1 trigger system will require a replacement of at least part of the tracking system and possibly a change in detector technology. Also, to find track stubs requires some association of data between different layers. This in turn requires readout of a fraction of the data off-detector, thereby introducing complications of cabling, power, and additional material in the tracking detector. The data rate for the barrel pixel has been estimated to be about 10 Gbit/cm^2/s, some reduction of the data to be readout would probably be required either on-chip or on-detector. One suggestion of how this could be achieved is via closely stacked sensors to create hit doublets before the off-detector readout. Another possibility is to implement specialized trigger readout for groups of pixels. A significant challenge is to keep the amount of material to a minimum, since the introduction of any additional detector layers or other material is a serious concern.

The maximum L1 rate and the maximum L1 latency are related, but separate, issues. Given the discussions in the working group, it should be pointed out that the maximum L1 rate is related to the readout time of the front-ends after a L1 accept, while the L1 latency is related to the maximum buffer depth of the detector front-ends.

The proposed increase of the L1 latency given in the CMS SLHC draft EOI is 6.4 μs, a doubling of the current 3.2 μs latency. An additional increase of the L1 latency is limited by cost. The L1 latency is limited by the front-end analog storage capacity of the tracker and preshower electronics, but these should to be replaced for SLHC running. Assuming that they are replaced, then the next limitation is the ECAL digital memory depth of 256 40MHz samples corresponding to 6.4 μs. Running at 13 MHz (75 ns bunch crossing interval) will not increase the latency since the ECAL has a fixed 40 MHz sampling. The ECAL front-end buffer is located on electronics attached to the back of a crystal and its replacement is not envisioned. The CMS SLHC L1 latency baseline is proposed to be 6.4 μs in the CMS SLHC draft EOI. This short L1 latency for accessing the trigger primitives, for track stub reconstruction, and for track stub association for track pattern recognition presents a serious challenge.

It is proposed in the CMS SLHC draft EOI to hold the L1 rate to 100 KHz to avoid rebuilding much of the front-end and readout electronics as much as possible. These were designed for an average readout time of less than 10 μs. Therefore, for the readout after an L1 accept, the maximum L1 accept rate should be 100 KHz. This limits any hardware level trigger that might sit between L1 and the HLT, like that proposed for ATLAS, at SLHC or used at CDF. Although such an intermediate hardware trigger could further reduce the rate of triggers going to the HLT, its use would be limited if the L1 rate could not be increased to take advantage of this. All it could provide is a redistribution of the same L1 rate between different physics triggers, as is the case for ATLAS.

Besides the challenge of developing an L1 trigger that is intertwined with the development of detectors, the DAQ, the cable plant and power considerations; an L1 tracking trigger also depends on changes introduced by upgrades of the LHC, for example, the beam crossing interval. Operation at a beam crossing rate of 80 MHz would require a rebuilding of trigger primitive calculations, and the CMS trigger system, and presents the challenge of possibly reading and reseting the pixel sensor every 12.5 ns.

The time scale itself is a challenge given the interdependency with the tracker system, and integration with other CMS components. The effectiveness of any L1 tracking trigger could be very dependent on the sensor technology and detector geometry, e.g. using pixels *vs.* short strips, using very small or large pixel sizes, using thick *vs.* thin sensors, using stacked layers *vs.* well separated layers. These may also govern what fraction of the tracking data can actually be used at the L1 stage. Depending on the exact trigger strategy or algorithm, the radiation damage of a detector can also be an important consideration. For example, radiation damage can affect the charge sharing in thick sensors.

A summary of the challenges for designing a pixel detector for use in an SLHC (Phase 2) L1 tracking trigger is given below.

- Keeping the data rate needed for L1 trigger primitives small enough to be brought off-detector for association of data between layers.
- Doing enough processing to have an effective L1 tracking trigger, but still staying within the L1 latency of 6.4 μs.

- Keeping up with reading and resetting pixels at a high beam crossing rate.
- Keeping within the material and power budget.
- Performing sufficiently detailed studies of enough trigger strategies soon enough to influence the new tracking system.
- Managing the significant interplay of the tracking trigger with design choices of the tracking system and other relevant CMS systems.
- Getting sufficient performance of an L1 tracking trigger given the constraints of the tracking system design, and the constraints imposed by other parts of CMS.
- Getting enough resources to produce a tracking trigger "technology demonstrator" for Phase 1.

Although the current CMS L1 trigger would be effectively "broken" at the SLHC (Phase 2), we believe it would not be broken in Phase 1. However, any replacement of some part of the tracking system for Phase 1, or the addition of new layers or disks gives us an opportunity to install a tracking trigger "technology demonstrator" for Phase 2 – either a proof of principle or a prototype for a larger system.

4 Status of Studies for an L1 Tracking Trigger

4.1 Stacked Trigger

A promising L1 tracking trigger strategy has been proposed for SLHC called "Stacked Triggers". The main idea is to use stacks of closely spaced sensors (SoI-MAPS) to quickly find mini-vectors to reduce by more than a factor of 10-100 the data that needs to be readout off-detector. This reduces power and cabling. Furthermore, with an appropriate choice of the separation between the stacked layers and pixel sizes, reconstructed mini-vectors would have to meet suitable minimum p_T requirements. This would be done using either one stacked barrel layer, or two sets of stacked layers. Two sets of stacked layers would be needed to infer the track p_T.

The idea of Stacked Triggers is illustrated in Fig. 3. Two closely separated layers of small pixels are used to find mini-vectors. These mini-vectors are defined by matching single hit pixels from the two layers, e.g. in ± zero or ± one pixel in phi (in the figure the match shown is for ± zero pixel in x). The choice of this matching "road" together with the pixel size and the layer separation determine the p_T cut and p_T threshold turn-on resolution, as well as the level of background rejection and thus data reduction. Two stacked layers are needed to infer the p_T of tracks. Use is also made of the z-location of hits. Further details on this the Stacked Trigger can be found elsewhere [8].

Although the proposed Stacked Trigger is a promising idea, from the work presented at the workshop it appears that a lot of additional work would have to be done to show that the idea can really work in a real detector under real conditions, and also be able to pass any external review.

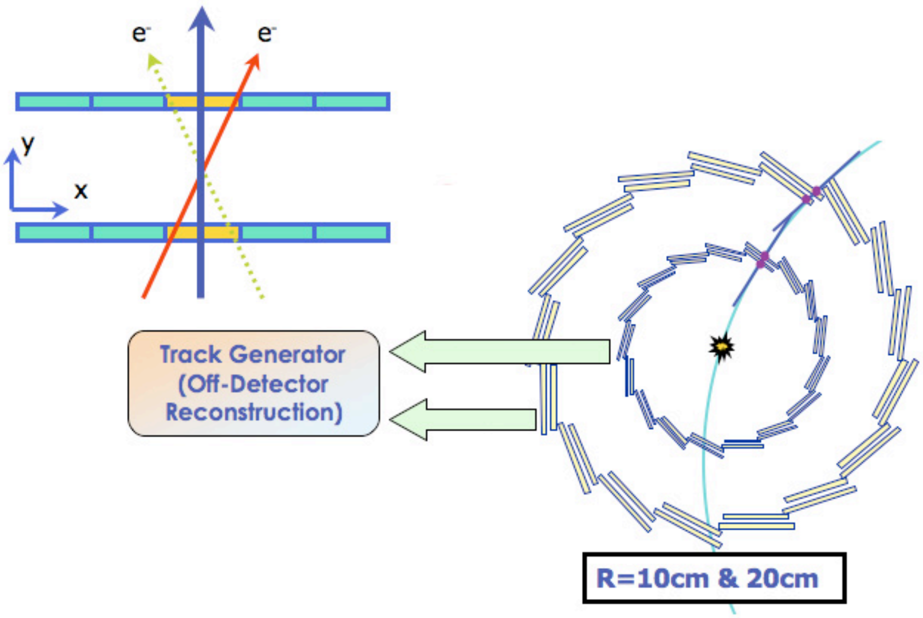

Figure 3. Illustration of the idea of Stacked Triggers.

The design of the Stacked Trigger scheme places strict requirements on mechanical aspects of the design. The pixel size needs to be small for this scheme to work. Various sizes have been considered such as 20 μm by 200 μm pixels, or 50 μm by 50 μm pixels. The sensor thickness must also be thin, on the order of 50 μm. These considerations constrain the type of sensor technology that must be used, and has implications for the alignment of the pixel system. The need for closely stacked layers is probably not ideal for offline track reconstruction, so this is not the most efficient use of the space available. Another major issue is that the studies that have been performed were done with a simple standalone Monte Carlo that omits many important effects that need to be simulated to properly evaluate the Stacked Trigger idea. Some of the things missing in the simulation include: Multiple Coulomb Scattering, and including all of the material in the simulation between the IP and each tracking layer; delta ray generation; charged sharing in a magnetic field; smearing of the beam spot; misalignment and miscalibration of the pixels; Poisson distributed pileup (with tails instead of a fixed number of pileup collisions); noise in the detectors; non-Gaussian tails; and realistic geometry (e.g. flat sensors instead of cylindrical ones and possibly overlaps with offsets in "r"). Fortunately all these effects can easily be included if use is made of the standard CMS simulation for further studies. These additional studies need to be done to demonstrate that the Stacked Trigger can work.

4.2 Other Initiatives

Other L1 tracking ideas have been presented at CMS SLHC workshops. One such idea from the Pisa group, but not presented at this workshop, is to use a more traditional regional track finding strategy similar to that used by CDF, for example, but using only the pixel hits [9]. Track finding is done in phi sectors and only in certain regions, using the z information and beam spot size. The simulations were done assuming full offline information for the pixels. The idea is based on the standard CMS L1 trigger philosophy of migrating HLT algorithms to L1 where possible. Although the simulations are more realistic in that the usual details are included, this trigger idea is less advanced than that of the Stacked Triggers, in the sense that little attention has been paid to solving the challenge of getting the full data off the pixel detector for processing at L1. One option proposed is to implement this trigger not at L1 but between L1 and the HLT, as is proposed for ATLAS (see below).

5 Further Tracking Trigger Ideas presented beyond that described in the CMS SLHC Draft EOI

Other ideas for tracking triggers based on geometries different from stacked layers were presented, like a fast tiny triplet finder based on BTeV experience, or pattern recognition in sectors as is done in CDF and proposed for ATLAS. Ideas for a pre-trigger that could be done after 3.2 μs and before 6.4 μs were presented and discussed during the workshop [10]. Also presented was the idea behind a proposal for ATLAS, and used in CDF, where a copy of the data after an L1 accept is obtained to perform a hardware-based L1.5 trigger that could redistribute the L1 100 KHz rate among different physics triggers. This would allow lowering of some thresholds at L1 for ATLAS for some L1 triggers while raising other L1 thresholds [11]. A similar idea, using constraint-based regional tracking in sectors with the full granularity for CMS, but at L1, was presented by members of the Pisa group in a past CMS SLHC workshop [12]. Another idea presented is the scheme used by the D0 L1 tracking trigger, where the trigger is divided into many radial sectors. For each radial sector, pre-computed track patterns for a few momentum ranges, taking into account the beam spot location and its size, are stored in FPGAs. The tracks hits in the event are compared to the preloaded track patterns to generate a L1 trigger for a given momentum bin within the sector.

Some of the ideas presented from offline reconstruction, like the reconstruction of mini-pixel vectors, might be of use as part of a set of L1 trigger primitives. These mini-pixel vectors are reconstructed using the pixel cluster shapes together with knowledge of the pixel charge sharing shapes. These mini-pixel vectors have shown to be useful for offline in reducing the pattern recognition load and may be interesting to investigate for an online trigger [13].

As mentioned previously, the inner layers of the silicon strip tracker may be replaced by pixel layers. However, one should consider not only the pixel detectors while developing the L1 tracking trigger, the use of some the silicon strip tracker hits together with the pixel hits should also be explored. It should be noted that just because some ideas, or the use of some information were not included here does not mean we are ruling out any particular options. We intend to be as inclusive as reasonably possible while making sure we also stay focused on our primary goal of making a L1 trigger that will work for CMS running at the SLHC.

5.1 Trigger Signals on the Existing BPIX and FPIX hardware

Only tracking strategies based on the barrel pixel have so far been studied. Ideas for using the forward pixel data in an L1 trigger still need to be studied. There has been no work on what L1 tracking trigger algorithm one could develop by using “existing” ROC barrel pixel trigger signals, or how well such an algorithm would work in SLHC. The availability of trigger primitives from the pixel detector is also an issue.

The pixel readout chip (ROC) includes a differential trigger primitive output [14]. The normal data for each sensor read out by a ROC consists of data for 52 columns (size 150 μm) and 80 rows (size 100 μm). The trigger primitives consist of double columns, and two thresholds can be used to configure these primitives: The first threshold is the number of pixels that must be hit in a double column for the double column to be considered “hit”; the second threshold is the number of double columns that must be “hit” for the ROC to output a trigger signal. The trigger signal is an analog output with the number of hit double columns encoded in it. This could be used for a multiplicity or jet trigger, but a segmentation of the size of one sensor/ROC maybe too coarse for effective track pattern recognition or even matching to a high p_T lepton. This should be studied before upgrades of the pixel system for Phase 1 running is finalized.

Another issue with using the trigger primitives is the availability of the output. For the barrel pixel the HDI routes the 16 differential trigger signals from the 16 ROCs to a central MTC (Module Trigger Chip). This chip has been designed in a 0^{th} version but has never been tested. It is currently not mounted, but besides acting as a signal concentrator, it could be used to do processing of the trigger data from the 16 ROCs. The output signals of the MTC would still need to be finalized and produced, but existing traces on the HDI can route these signals to the module signal cable (21 traces in total) and end up in ZIF plugs at the endflange that is currently under design. That’s where the signals end and nothing has been implemented to bring the signals onto the supply tube and to extra optical links (which do not exist either). The availability of the ROC trigger signals is worse for the forward pixel system. The trigger signals in the FPIX ROC end in the HDI for each panel. There is no provision for a MT chip, or traces to bring the output to the edge of the HDI, and of course no cables are available to bring the signals off the detector either as in the case of the BPIX. It is unlikely that one could get the trigger signals off the FPIX detector without rebuilding the FPIX panels [15].

6 Existing Software Tools

It seems obvious that a significant simulation effort is needed. We describe the existing tools in CMS that could be used for the studies required to evaluate and demonstrate the effectiveness of any L1 tracking trigger strategy or algorithm. As far as possible if the existing CMS software tools can be used for our studies, or could be used with a relatively small effort, it is preferable to do this and thereby contribute to the main CMS tools rather than spend time developing external ones.

A fully functioning simulation of the CMS detector based on Geant4 is available in CMSSW_1_1_0, including pileup. Reconstruction of tracks and high-level objects are also available in this version of CMSSW. Currently the only general purpose generator available is Pythia, though other more specialized generators like MadGraph, CompHEP, TopRex, StaGen, Charybdis, or a particle gun are also available. The interaction point can be smeared by a Gaussian distribution using the official code, but additional user code is needed to simulate a crossing angle or an hour-glass effect. These features should be straightforward to implement.

The geometry for the tracking system, like the rest of the CMS detector in the simulation is complete. Some work is ongoing to update the materials for the forward pixels but this need not interfere with any studies needed for SLHC. The geometry is fairly modular, and structured in a hierarchical fashion, where each part is specified by an XML file. Changing the geometry requires understanding the detector description language (DDL) used in these XML files. Moving existing pixel components around, like layers, disks, plaquettes or panels are fairly easy to do, and the simulation need not be changed except for a piece of code that maps sensor positions with detector IDs (the numbering scheme). Changing the pixel size and sensor thickness is also very straightforward, as only the digitizer needs to be configured to handle these changes through a configuration file. For more radical geometry changes one has to learn DDL and created new Geant4 volumes. This takes some learning but again, for simple geometric shapes this is not so difficult and we have expertise in the forward pixel group. For SLHC studies, we would include all the necessary material, but would initially try to use simple geometric shapes when defining volumes. Also for new volumes we would not initially include some of the complexities we have in the standard FPIX geometry, like individual nipples on each blade, but just average out the material in some simple geometric shapes. We will call these simpler detector layouts, “toy geometries”. These toy geometries will have fewer components and simpler shapes but they should be suitable for fast comparisons of different possible geometries. Once the XML files are created for one such toy geometry it should be possible for other non-DDL experts to modify it to study variations of particular toy geometries.

The only tool for checking and testing the geometry is Iguana, which is a version of the standard CMSSW executable that is used for Geant4 visualization. One can use this to check the geometry visually, except for Boolean solids, which seem to have a flaw in the implementation. The only way to really test if the geometry is correctly simulated in the

Monte Carlo is to manually run a simulation and check the output. This is probably sufficient for at least initial studies.

For the pixels, the simulation provides "simhits". These are space points in local (sensor) coordinates for entry and exit locations in the sensor, and include the energy deposited. Note that at the simulation (Geant4) stage the whole sensor is simulated as a single volume. Individual pixels are not simulated at this level. Separate digitizer code is used to convert these simhits to get "digis" which give pixel hits in local coordinates and the charge deposited in ADC counts. The charge sharing code accounts for the magnetic field and calibrations. Knowledge of the global geometry is necessary at this point to get the correct magnetic field for charge sharing. A further routine is used to make "rechits" which are clusters of pixels, also in local coordinates. Only at the track reconstruction stage are the rechits relocated in global coordinates. This means that it would be easy to change the geometry without needing to change the digitizer or rechit generator code.

Though not part of the official CMSSW reconstruction code, there is a "PixelNtuplizer" that takes the simhits and uses the official CMSSW digitizer and rechit code to produce a file of rechits located in local coordinates. This file of rechits, if trabslated to global coordinates would be extremely useful for people who want to just try out pattern recognition and tracking algorithms in their own "sand-box", and thus reduce the overhead for new people to get involved in investigating pattern recognition and tracking algorithms. However, to understand reconstructable events one would need some way of doing the tracking and analysis with this rechits output file. A prompted tracking program may be sufficient instead of full track pattern recognition for comparisons of different trigger algorithms. Comparisons would be based on efficiencies for particular physics signals *vs.* rejection of min-bias events.

The Iguana visualization seems to be very difficult to use for visualizing hits and tracks to study pattern recognition problems. This is because of reported instability issues, and the absence of a feature that lets a user save settings in a configuration file. If the PixleNtuplizer was used to create an external rechits collection in global coordinates, one could easily visualize the hits in some other way. A rechits and track visualizer would be useful for debugging and studying what is going on when pattern recognition problems arise.

Besides the full simulation, CMS also has a fast simulation, FAMOS, however this is not yet completely ported to CMSSW, the new CMS framework. We propose that in future simulations we use CMSSW rather than the old framework. We have to investigate the ease of use of FAMOS for the various simulations studies that are needed.

Enough simulation samples will need to be generated. CMS already has a mechanism for simulation sample production, and we should just try to use this for generating enough samples for SLHC studies.

7 Requirements for L1 Tracking Trigger Studies

Detailed simulation is the key for developing an upgraded pixel detector and L1 tracking trigger for SLHC that achieves the physics objectives of CMS. Geometry and detector simulations are needed, as are analysis tools to study both trigger performance and the impact of a tracking trigger on physics analyses. Optional tools such as visualization software can be useful in the development of an L1 tracking trigger.

Ideally the development of an L1 tracking trigger should involve the **evaluation of several different trigger algorithms**. These algorithms should be evaluated by studying rejection of minimum bias events with the level of pileup that is anticipated for SLHC in different operating scenarios, and should demonstrate acceptable trigger performance by calculating signal efficiencies for specific final states that are considered crucial for CMS physics.

At least two approaches are possible to perform simulations for trigger studies. One approach is to take advantage of the machinery that is under development for CMS physics analyses including CMS event generators, GEANT simulation of the CMS geometry, detailed detector simulations that include all material in detector subsystems, and the CMSSW analysis and visualization environment. A second approach is to use a fast parameterized simulation and analysis environment that permits quick changes to detector geometries without having to recode analysis software. Using a fast, parameterized simulation has the advantage that pixel and tracking detector designs that differ significantly from the current CMS detector can be evaluated easily, but this approach suffers from the lack of detail that is available in currently existing CMS simulations, reconstruction and analysis software. One of the conclusions from the CMS Pixel Detector Upgrade Workshop is that many (if not most) of the tools needed for pixel detector and trigger simulations are available today. Ease of use of existing tools and development of additional tools will require further evaluation.

Trigger studies should take advantage of the complete geometry of CMS wherever possible. This is referred to as the **reference geometry** for the purpose of comparisons to other geometries. In some cases a simplified geometry may need to be implemented when details of a proposed pixel detector design are not available.

The following capabilities are required to perform the simulations and studies that will be needed to develop, design, and validate an L1 tracking trigger for SLHC.

7.1 Geometry Studies

Development of a new pixel detector for SLHC, optimization of a proposed geometry, and the evaluation of different trigger algorithms will require changes to the existing CMS geometry. These geometry changes are expected to include the following: introduction (or removal) of pixel or tracking detector layers (for example, the introduction of a “stacked” pixel layer for triggering), simplified geometries to evaluate new types of pixel detector technologies, introduction (or removal) of material associated with support structures, cabling, cooling and power.

A flexible geometry specification that is relatively easy to manipulate is required. The CMS Detector Description Language (DDL) implemented with XML appears to be adequate in that it allows very complex geometries and implementation of simplified geometries. Replication of detector subsystems is accomplished through the use of "algorithms." Visualization and verification of the implementation of a specific detector geometry is accomplished by using Iguana.

7.2 Detector Studies

Trigger studies will require the evaluation of many details of proposed pixel detectors. These include pixel size, sensor size, configuration of sensors in modules, and overlap schemes to name a few. Optimizing the design of an upgraded pixel detector within the context of an L1 tracking trigger will depend on simulations that demonstrate detector and trigger performance.

7.3 Pixel Detector Simulations

Detailed pixel detector and readout-chip simulations are crucial in the design of an L1 tracking trigger that depends on pixel data. Simulations of charge collection and charge sharing for adjacent pixels including effects from low-energy delta rays are important when one considers the trigger response in a high-rate environment such as CMS. These simulations should also provide input to simulations of pixel readout-chip designs to study data rates out of the chip and into the L1 trigger hardware.

7.4 Studies of Different Accelerator Operating Scenarios

A complete set of simulations needs to be performed to study the performance of pixel detector designs and trigger algorithms for different accelerator operating scenarios and varying beam conditions. Of primary importance is the LHC bunch crossing time, proposed values range from as low as 12.5 ns to as high as 75 ns in different scenarios. Studies will need to be performed for proposed changes to the luminous region of the IR, and changes in beam position over time. While certain proposed scenarios are likely to be unrealistic, one should expect requests for studies of detector and trigger performance for different operating conditions.

7.5 Trigger Performance Studies

Each L1 tracking trigger algorithm that is proposed for SLHC will need to satisfy studies of trigger performance. Algorithms will need to be tested with regard to rejection of minimum bias interactions with varying degrees of pileup anticipated for SLHC, and must demonstrate required trigger performance for specific final states considered that are representative of crucial measurements for CMS physics. Trigger algorithms must also be evaluated with realistic detector efficiencies, and trigger performance must be determined in an environment with noise levels that exceed design specifications.

7.6 Simulation and Analysis Tools

A number of simulation and analysis tools will be needed to study proposed L1 tracking trigger algorithms, develop a baseline design for a tracking trigger, and evaluate performance characteristics. The ability to generate many different signal and background data sets for different accelerator operating conditions, different detector geometries, and different types of pixel detector designs is important. Some of the capabilities that will be needed are the following:

- rudimentary event display to explore and develop new trigger algorithms
- visualization software to verify implementation of detector geometries
- ability to write files with pixel hits in global coordinates
- ability to write files with silicon strip tracker hits in global coordinates
- match trigger primitives and reconstructed tracks with MC tracks
- modify beam conditions in the simulation code
- ability to implement different models for charge sharing in pixels
- ability to implement different levels of noise in the pixel system

An important aspect of the simulations needed to develop a CMS tracking trigger for SLHC will be the use of **common simulation and analysis tools**. This will be important when comparing results obtained for different detector designs and different trigger algorithms.

8 Proposed R&D Plan for an L1 Tracking Trigger Using the Pixel Detector

One of the goals of the CMS Pixel Detector Upgrade Workshop is to develop an R&D plan for the Pixel Group that can be aligned with R&D efforts in other groups. An important aspect of the overall R&D plan is that it should acknowledge the interdependence of developing an upgraded pixel detector, upgraded tracking detector, and the introduction of an L1 tracking trigger for SLHC.

We present a proposed R&D plan for the Pixel Group to contribute to the CMS SLHC effort. This R&D plan is given to provide a basis for discussion and to help with the planning process. This plan is based on experience obtained from ten years of R&D devoted to the development of a pixel-based Level-1 tracking trigger for the BTeV experiment. After an initial period of three to six months devoted to help establish a pixel group to work on SLHC upgrades, the plan identifies three high level activities: "Algorithms and Simulations," "Trigger Design," and "Trigger Prototyping." Assigning these particular names to the high-level activities should not suggest that these would be the only activities that would occur during a particular period. Instead, the name of the high-level activity suggests the primary focus during that period in time. For example, during the two-year "Algorithms and Simulations" phase the emphasis would be on developing a baseline algorithm that satisfies the requirements of an L1 tracking trigger. Efforts geared towards exploring possible trigger designs and initial efforts in prototyping hardware are likely to occur during this period as well. However, the primary focus would be on developing the algorithms and simulations that would lead to a baseline algorithm that meets CMS SLHC requirements.

8.1 Help Establish a Pixel Group for SLHC (3 – 6 months)

Help establish a Pixel group that will work on developing and contributing to the CMS SLHC L1 tracking trigger:

- Identify new and existing group members to help form a unified working group
- Identify specific physics analyses to make the physics case for a tracking trigger
- Collaborate with CMS tracking, trigger, and DAQ SLHC groups to help establish (joint) requirements
- Contribute to SLHC Expression of Interest (EOI) and SLHC workshops
- Evaluate suitability of CMS simulation software for trigger studies
- Edentify tools that will be needed, and begin development of those tools

8.2 Algorithms and Simulations (2 years)

Develop and evaluate L1 trigger algorithms using the BPIX and FPIX together with the other CMS SLHC groups and perform simulations. This phase corresponds to the "Monte Carlo" phase for the "Full Tracker" in the CMS SLHC Expression of Interest (EOI).

- Perform studies and simulations outlined above
- Refine simulations as CMS data becomes available
- Evaluate different trigger algorithms
- Select a baseline trigger algorithm (**milestone**)

8.3 Trigger Design (2 years)

Participate in the development of the baseline L1 trigger using the BPIX and FPIX in collaboration with other CMS SLHC groups. This phase corresponds to the "Concept" phase for the "Full Tracker" in the CMS SLHC Expression of Interest (EOI).

- Develop hardware design to implement the baseline L1 trigger
- Update L1 trigger algorithm as detector design develops
- Use CMS data to refine the trigger design

8.4 Trigger Prototyping (2 years)

Develop trigger prototype hardware and implement hardware for a Phase 1 "technology demonstrator" if possible. This phase is not explicitly mentioned in the CMS SLHC Expression of Interest (EOI).

9 Summary and Future

We had very productive working group sessions in this workshop, discussing the possibility and design of a L1 tracking trigger using an upgraded pixel detector. We made progress on outlining what we need to work on in the near future and made a first attempt at defining some requirements and a longer term R&D plan. We hope to continue this momentum after the workshop. Many people have expressed an interest in participating in the work needed to develop an L1 tracking trigger. These people are listed as authors of this report.

For the immediate future we propose the following tasks:

- Identify new group members and help establish a unified working group with those CMS SLHC members already involved in the R&D for an upgraded pixel detector or tracking trigger.

- Setup a "toy geometry" for a CMSSW simulation with a Stacked Trigger layer added to the standard CMS geometry to enable more realistic simulations of the Stacked Trigger idea.
- Perform more realistic simulations to evaluate the performance of currently proposed L1 tracking trigger schemes.
- Setup a "toy geometry" that uses less complex geometrical shapes for detector volumes within the pixel and inner strip tracker volume. This geometry file should be documented to a level where a non-DDL expert can easy modify simple parts of the geometry, and would be the basis for non-experts to do various simulation studies.
- Help develop tools that will enable someone to work on hit and track pattern recognition without the overhead of having to learn the whole suite of CMS software, or having to deal with problems that might arise with frequent changes to the CMS software version. Initially develop code to the output the collection of rechits from both the pixel and strip tracker systems in global coordinates.
- Investigate the status of FAMOS, and the ease and suitability of its use for the simulation studies needed.
- Identify people to work on the different tasks and help them make progress.

Following the Roadmap given in the draft EOI, we should participate in the CMS SLHC workshops, and in particular, join the "Pixel system and triggering working group" that will soon be formed as part of the CMS SLHC effort [16].

It is important that we stay focused on the main goal of showing that we can get the required performance for a L1 trigger at the SLHC for high p_T physics, and other physics that might be important during SLHC running. This will require the use of present software tools for doing the more detailed studies that are needed to ensure that any proposed tracking trigger will work at the SLHC. We should also improve the tools, when needed, or develop new tools, if required. There are people who are interested in contributing to this main goal. These software tools can in turn be used for studies of other tracking trigger strategies for high p_T physics or even optimizing the triggering of other physics that people are interested in.

Although the primary purpose of this working group was to set requirements for the pixel detector that can be used in an effective L1 tracking trigger, as noted by everyone throughout this workshop, the design of all the different components: pixel detectors, readout, trigger, DAQ, construction and assembly, are all inextricably linked. Progress must be made in the R&D for a L1 tracking trigger in parallel with the design of the pixel detector. For the moment we believe we can provide very little guidance to pixel-detector designers on a specific implementation for a pixel tracking system. We should revisit this in a time frame of 6 months to one year.

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[1] http://www.uscms.org/fpix/pixel_wksp_06/
[2] http://www.uscms.org/fpix/pixel_wksp_06/Oct06_Charge_v2.pdf

[3] http://cmsdoc.cern.ch/cms/electronics/html/elec_web/common/slhc.html and http://cmsdoc.cern.ch/cms/electronics/html/elec_web/docs/slhcusg/slhc-eoi-0.95.pdf

[4] http://indico.cern.ch/conferenceDisplay.py?confId=6904

[5] See talk presented by Jordan Nash at this Workshop, slides located at http://indico.cern.ch/materialDisplay.py?contribId=1&materialId=slides&confId=6904

[6] http://cmsdoc.cern.ch/cms/TDR/DAQ/daq.html page 308.

[7] See talk by Sridhara Dasu, slides located at http://indico.cern.ch/materialDisplay.py?contribId=13&sessionId=1&materialId=slides&confId=6904

[8] See talk by John Jones, slides located at http://indico.cern.ch/materialDisplay.py?contribId=14&sessionId=1&materialId=slides&confId=6904

[9] See talk from Fabrizio Palla and Marcel Vos, slides located at http://indico.cern.ch/materialDisplay.py?contribId=s1t5&sessionId=s1&materialId=0&confId=a053123

[10] See talk from Jin-Yuan Wu, slides at http://indico.cern.ch/materialDisplay.py?contribId=15&sessionId=2&materialId=slides&confId=6904

[11] It was noted after the workshop by Wesley Smith that the basic design as stated in the draft CMS SLHC EOI is to read out all detectors to BU/HLT nodes directly after L1, thus a L1.5 trigger similar to the ATLAS proposal would not be accommodated.

[12] See talk by F. Palla and M. Vos, slides located at http://indico.cern.ch/conferenceDisplay.py?confId=a053123

[13] See talk by Kevin Burkett, slides located at http://indico.cern.ch/materialDisplay.py?contribId=18&sessionId=3&materialId=slides&confId=6904

[14] Alan Hahn, private communication.

[15] See talk by Alan Hahn, slides located at http://indico.cern.ch/materialDisplay.py?contribId=42&sessionId=2&materialId=slides&confId=6904

[16] See email from Geoff Hall to Tracker Group, or the link http://cmsdoc.cern.ch/Tracker/Tracker2005/TKSLHC/Tracker SLHC working groups.htm