CMS Upgrade MB Response to SLHC Document:

09.03: Proposal for Phase II Tracker and Trigger Planes based on Vertically Integrated Electronics

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We believe that this proposal should be restructured into two steps. The first step should include (a) generic R&D (e.g. vertically integrated chip, thinning technology, TSV, DBI, bonding methods, power) for future application, which culminates in a demonstration proof-of-principle and (b) simulation studies contributing to layout decisions. The second step should include the CMS-specific R&D and be fully integrated with the CMS Tracker upgrade project. The second step should require achievement of the demonstration milestones of the first step as well as input from the simulation studies in order to proceed. This should be subject to review by Tracker Project Management. The proponents should work with Tracking Project Management in the development of the revised proposal and the Tracking Project Manager should review the revised proposal.

Specific requests for the revised proposal are:

Step 1 (a) – Does the basic technology work:

1. Provide a plan with the specific milestones of:
   - Prototyping and characterization of 3 building blocks: VICTR chip, Sensor, Interposer
   - Assembly and characterization of VICTR chip + sensor
   - Assembly and characterization of Interposer + sensor
   - Assembly and characterization of full 3D module: VICTR chip + Sensor +Interposer + Sensor.
2. Provide more details on the interposer:
   - Can it be made 1-2mm thick?
   - What will be the production yield for 2 mm long vias?
   - What will be its contribution to the material budget?
   - How will the "Swiss-cheese" design work?
   - How will the data transmission be solved for tracks that cross the detector at an angle far from 90 deg, or at a very different z?
   - Does it distribute power, detector bias, control signals and the data readout? How?

N.B. The above points are considered to be of higher priority in the short term than the beam and radiation testing.

Step 1 (b) – Can this technology be made to work in a real tracker:

3. Provide a plan for the necessary simulation studies of the physical layout options, pixel dimensions, stacking designs, etc.

4. Provide a plan to fast-track studies of the thermal budget of 3D stacks, the yield and scalability.

Step 2 – Can such a tracker be built:

5. Provide a plan to provide tested integrated circuits and other components prior to module assembly, including provision for testing procedures to assure inclusion of known good chips and components.
6. Provide a plan to integrate and test the 3D structure comprising sensors, electronics and interposer as it is being assembled.
7. Provide a plan to design the distribution of the low voltage power (and filtering), control signals, clocks and asynchronous digital readout busses, including the requirements on these systems.
8. Provide a plan to design of the data transmission between layers in stacks that includes evaluation of via density.

Referee #1:

1) The R&D presented in proposal 09.03 is appropriate for the needs of CMS at SLHC. It is ambitious and risky, but given the uncertain timescale for phase 2 upgrades, it is worth pursuing.

The first 3 sections of the proposal describe the developments of an integrated stack of sensors, chips and interposer. 3D integration is a promising technology with a disappointingly slow convergence speed. An R&D activity in this domain will allow the community to better assess the risks associated to the speculative areas of the proposed concepts. Apart from the described integration challenges, I would recommend that some effort is devoted to studies of the thermal budget of 3D stacks (before going into mechanical prototyping and cooling studies), and to analysis of yield and scalability issues. It is in particular important to understand whether this technology will grow to wafer scale and be suitable for square meter scale assemblies.

Sections 4, 5 and 6 of the proposal describe radiation hardness tests, mechanical prototyping and simulation considerations. These are important aspects but I am not convinced they need to be addressed specifically and independently at this stage. These activities would benefit from being carried out in full synergy with the rest of the tracker collaboration, with tight links to the layout and simulation working groups.

In my opinion, the R&D is not focused enough, as presented, and would benefit from re-centering on the 3D integration challenge only.

2) Phase 2 upgrades are far into the future, and it may not be unreasonable to allow at this early stage some duplication of effort in an open and coordinated way. With this in mind, I would not use the duplication of effort argument against this proposal. I would however recommend to ensure a very tight collaboration within the existing tracker working groups, a challenging coordination task indeed.

3) The highest priority activity is the integration of a 3D structure comprising sensor(s), electronics and interposer. This is generic enough to be carried out as a standalone R&D project. The interposer is a critical element of the proposal, and this effort would benefit from additional resources; the interposer work plan in Table 2 stops at the end of 2009 and has no budgeted resources in table 3. This is probably unrealistic, and might result in the delivery of only homemade prototype demonstrators. I recommend consolidating this activity and identifying industrial partners early in the project (and not in a second phase as proposed). In technical terms, the yield and electrical/mechanical reliability of stacked interposer wafers with plated through vias (not filled) is a concern. This issue deserves a long-term test program. The VICTR chip, an adaptation of the ATLAS pixel front-end amplifier/discriminator, is a good starting point. I didn't understand from the proposal if Cu-Cu bonding of two tiers will be attempted (Fig. 4). This might need to be clarified to assess the overall risk of the project. As mentioned under point 1 above, I would recommend to study the thermal budget of the integrated 3D stacks and to analyze the yield and scalability of the assemblies.

Radiation hardness tests and mechanical prototypes are a second priority. The mechanical work needs input from the tracker layout task force and should not proceed in isolation. The investigation of double stacks could progress in relative independence, but apart from Fig. 10, I see no details of that concept in the project description or in the deliverables list. The radiation testing can be postponed to a later stage, as I don't see major unknowns on that front.

4) Assuming the project focuses on 3D assemblies, obvious milestones are:

- Prototyping and characterization of 3 building blocks: VICTR chip, Sensor, Interposer
- Assembly and characterization of VICTR chip + sensor
- Assembly and characterization of Interposer + sensor
- Assembly and characterization of full 3D module: VICTR chip + Sensor +Interposer + Sensor.

Referee #2:

I would like to make clear that this is obviously a very complex proposal, with an ambitious and potentially revolutionary approach to make a new tracker, therefore at this stage I thought that it would be better to concentrate on few key aspects, and forget about minor, but potentially also important, details.

In general, clearly this is an extremely interesting proposal because 3D integration, if proved successful, could really revolutionize the way we conceive detectors in the future and in my opinion it is extremely important that a strong group of people in our community carry out sufficient research to explore this route fully. On the other side, the technologies required are so sophisticated that we have to prove that we - as a community - will be able to master the inevitable difficulties and complexities of what will be required. These technologies will definitively be introduced sooner or later in volume manufactured commercial products, and how to use these technologies for our benefit still remains to be fully understood. Therefore CMS should in my opinion definitively invest and support a proposal of this type and monitor carefully its development, trying to match the developments in the field with the schedule and requirements of the calendar of the upgrade.

The first comment concerns the lack of a strategy, at least in this document, for providing tested integrated circuits prior to module assembly. Although the final module size is not clearly given in this document, it is clear that a full tracker requires to start with building blocks of a reasonable sizes. Modules for a 10-20 m2 detector should probably be at least in the 5x5 cm2 range and will require several chips to be assembled together. I believe the proponents should say how they plan to make sure that these chips are "known to be good" prior to final assembly with the detector on a module. I would like to clarify here that, when using TSV for critical connection to the chip, certain signals will only be available when the vias will have been opened and metalized, and this could be a serious problem for chip testing. It is clearly impossible to assume that a 10-20 chips module could be assembled without 100% tested chips, and the proponents - in my opinion - should have a look at this aspect early in the project.

The second aspect that perhaps requires more attention is related to the power and control signals distribution in a module built with the proposed architecture. I have the impression that the only possible carrier for these signals is the interposer itself. Now this element also has to carry the detector signal from the "top" layer to the read-out chip and these signals must not be disturbed by power or control signal induced noise. Surely the interposer in the module will have to carry clock signals and asynchronous digital read-out buses. I have the impression that this could be a significant problem for the architecture proposed or that at least the proponents should explain how they intend to solve this problem.

Now, answering your specific questions:

1) The R&D is appropriate for the needs of CMS at SLHC (i.e. focused)
Yes, this is a very significant proposal for CMS
2) The R&D is not excessively duplicated (i.e. we don't have too many people have working on the same topics)
No, I believe that this proposal is sufficiently different from other that it does not constitute an unnecessary duplication of work. Perhaps some of the work on sensors could instead be shared with other proposals

Following consultation with Tracker Project Management, we would also appreciate your views on:
3) Of the R&D proposed, (a) which are the highest priority?
See the two issues mentioned in the above paragraphs,
(b) which can be identified as generic (e.g. independent of the specific tracker design selected)?
I guess that this proposal has to be focused on specific tracker needs to make it successful, being generic would not really help as the key technologies to be developed are fully focused on a tracker detector.
(c) which need input from simulation in order to proceed?
(d) which need input from other R&D (not included in the proposal) in order to proceed?
4) Suggested milestones or checkpoints where progress and plans for continuation should be reviewed.
This is a difficult question, as the upgrade calendar seems to be such an elusive entity anyway and setting too tight milestone may prove unfair to the project. I would guess that early small

demonstrators could well prove successful for such a proposal, but that difficulties may arise at late stages when large systems will have to be assembled out of the technologies proposed. It may be important that specific system issues are answered early rather than late as to avoid stalling the project at a late stage.

Referee #3

Introduction

The most difficult problem of a tracker trigger for CMS is the requirement to transfer high data volumes.
All other problems, like data processing, detector technology, etc. are secondary.

The present proposal has two main aspects:
1) the concept to estimate the track pt by using closed spaced tracking layers.
2) the idea to use 3D electronic circuits to solve the problem of large local data traffic.

Part (1)

The closely spaced layer concept is widely accepted as a good candidate to make a fast estimate of the pt.
The layers should not have too small radii in order for the tracks with different pt to have a significantly different crossing angle. The radii should also not be too large in order to limit the cost. Another important optimization factor is the distance between the layers.
This proposal is based on 2 layers at 25 and 35 cm with the distance between the layers between 1-2 mm. Both sets of number should be studied more in simulations in order to determine their best values. The authors propose to carry such studies.

Part (2)

The 3D electronics is a new concept for integrating electronics in tracking detectors. It seems especially suited for connecting 2 layers 1-2 mm from each other. It might offer the only chance to transfer locally the large amount of data needed for triggering. Therefore this technology is worth pursing. It is impossible to say today if it will be suitable for a full scale CMS tracker layer but it is worthwhile to start an R&D project to build small-scale prototypes and test them. Below are a few additional comments.

A) Interposer This item is one of the more important components of the proposal. Several questions need to be answered before:
A1. Can it be made 1-2mm thick?
A2. What will be the production yield for 2 mm long vias?
A3, What will be its contribution to the material budget?
A4. How will the "Swiss-cheese" design work?
A5, How will the data transmission be solved for tracks which cross the detector at an angle far from 90 deg, that this from very different z?
A6. It is not clear from the proposal if the Interposer is also supposed to distribute power, detector bias, control signals and the data readout.

B) Double stacks

To achieved the proposed 20GeV pt cut the two double-layers are separated by 10cm in radius. The signals from the two layers in the stack have to be combined in order to form the trigger information. The proposal does not address this problem in depth. It only shows a sketch in Fig. 10 from which it is not clear how the large amount of trigger data will be transmitted. Especially combining information from several modules (rings) in z is not explained. With the two stacks separated by 10 cm and tracks coming from different vertices in z there will be a need to combine information. More concrete plans concerning the data transmission should be included in the next stages of this proposal.

Activities

Activity 1:

This part of the proposal is quite complete and it is clear what the authors want to do. It probably has big chances to succeed.

Activity 2:

The proposal is clearly outlined. It is not hard to say what the chances of success are but it is worth pursuing it as an R&D project.

Activity 3:

This part is very vague. Before a detailed mechanical design is made the results from Activity 4 should be known.

Activity 4:

No details about the trigger data flow are given. The main problem of the large data flow is not addressed. The part about simulations is clearer and is obviously needed.

Activity 5 and 6:

Beam and radiation testing is part of every detector design, but before starting extensive beam tests the basic functionality of the trigger modules should be established.

Summary

The presented proposal is worth accepting as an R&D project for the CMS tracking trigger. It should answer the question, if the 3D technology is worth pursuing for a large-scale detector, and also estimate what the cost and production yield?

Before a full-scale project is started a more detailed trigger architecture plan should be presented. As mentioned above, the most essential problem for all tracking triggers are the data rates. This has to be addressed also for this proposal, especially the communication path between the two dual-layers. The particular choice of the sensor and readout chip technology is less critical.

Some more work is also needed for simulation work to improve the layout choice, especially concerning the dual layer separation and the distance between the two dual layers.

Referee #4:

The authors propose to study the feasibility of tracking and trigger planes based on 3D integrated electronics. This is a rather new technology that has not yet been used in the construction of tracking detectors. On the other hand this technology is pushed by industry because of its huge potential in ASIC integration. Therefore one can hope that this technology will develop rapidly and that we can profit from its development. If proven to work, 3D integration would open up very interesting options for detector development. The currently proposed double layers for triggering at SLHC are just one example. Given that we should try to make best use of the available techniques for the construction of the SLHC tracker I think that this R&D proposal is very interesting and very relevant. Still it is based on a completely new technology and therefore success is not guaranteed and it is difficult to estimate the time it will take before this technology is mature and before CMS could eventually rely on this development as a baseline for the future tracker.

The proposed R&D program is well focused on the development and test of the 3D interconnects, the read-out ASIC, the "interposer" as well as the module and rod design with the aim to have a 3D prototype module available and tested before the end of 2011. This is an ambitious planning. It would provide results on the key issues well in time for the tracker upgrade TRD that is currently foreseen for 2012. Since (at least to my knowledge) nobody else in CMS is working on 3D integration this R&D is unique and generic. In this respect the 3D interconnect clearly is the most important aspect of this R&D program. But since the opportunities which are opened by this technology are really unique it is very reasonable to complement this development by a program on the development of a module and rod concept which makes full use of the advantages of the new technology. Consequently the proposed R&D is to a large extent fully parallel to other trigger module concepts that are being discussed. Still, the authors wish to make use of the ongoing R&D on DC-DC powering and CO2 cooling.

The collaboration behind the proposal seems powerful enough to carry out the proposed program of work. The funding situation remains a bit unclear. Since this program of work relies on several companies for key developments it would be good to know that the required funds are or will very likely be available.

The list of milestones presented in chapter 8 of the proposal seems reasonable and should allow monitoring progress. The "preliminary schedule" for these, as presented in table 2, is ambitious and failure to meet this schedule would not automatically render the development unsuccessful. Once the basic technologies have been checked and before larger prototypes or second generations of ASICs are started it has to be evaluated if a tracker can be constructed based on these technologies. The CMS tracker should review the proposal at this point. A concept is needed for the on-module combination of the signals from the two layers of a stack and for the data transmission off module. These issues are only very briefly mentioned in the proposal and would need to be much better defined at that stage. Likewise there is no estimation of the power dissipation of such a module design and the associated links for off module communication. An estimation of the material budget is missing as well. The authors should be asked to provide (as a milestone) this information at the latest when the viability of the basic technologies has been checked. According to their schedule this would be around mid of 2010.

On a more technical level I am missing information on how the low voltage is distributed and filtered in such a module (i.e. without a hybrid). I would appreciate if this issue could be clarified.

In summary and with the requirements stated above I recommend accepting this R&D proposal. 3D integration could turn out to be a key technology in five years time. CMS should explore this technology and this R&D proposal is a good way to do this.

Referee #5:

General comments:

Trigger issues at high luminosity will be very challenging, based on what one already knows today, and could turn out to be much more challenging after some operational experience with beam. More likely than not, either smarter ideas or new technology or both will be needed in order to really meet the trigger challenges in the future at LHC. Because of that, it is wise to keep an open mind at this stage when thinking about the trigger upgrade issues, esp. for Phase II at SLHC.

Current plan for Phase II is to use tracker information at Level 1, with the basic idea of selecting high Pt tracks based on either hit cluster width or hits projectivity of two closely spaced sensor planes to the interaction region. One of the key issues with the latter approach is how to implement a "local" trigger capability to reduce the number of hits to be read out. Since the emerging 3D chip technology could potentially be used for vertically integrated sensor and readout planes, the proposed R&D to study the feasibility of tracker/trigger planes is appropriate for the needs of CMS trigger upgrade at SLHC.

Of the R&D proposed, it seems that the highest priorities would be to demonstrate the thinning and TSV technology, followed by bonding. As far as the 3D concept goes, the thinning and TSV technology as well as bonding can be identified as generic. In addition, the proposed vertically integrated structure doesn't seem to assume any specific layout of the tracker design.

The highest priority items (to demonstrate the thinning and TSV technology followed by bonding) do not need input from simulation in order to proceed. The design details of the vertically integrated structure, including the concept of long/short strip sensor layout, the interposer, the via density, and VICTR chip design choice etc, as well as system level issues (such as number of fibers etc) will need inputs from detailed simulation as well as knowledge on hardware limitations to be gained through the R&D efforts. Of course, the simulation will need to be confirmed/calibrated by data as soon as beam data become available.

It is not so clear as to why the VICTR chip is designed in such a way at this early stage that requires pairs of wafers bonded together face-to-face. Since each extra manufacturing step adds risk for defects and thus yield, naively one would think that it is more desirable to keep things simple enough (single layer instead of 2 layer design for VICTR chip) in order to make more steady progress. Of course, I am sure that there are very good reasons the VICTR chip is designed this way, it is just not so clear from reading the proposal.

It is worth noting that there isn't much discussion in the proposal on power requirement, delivery and design issues for the vertically integrated structure and its implications to the overall design. In addition, it will be useful to have some discussion on system level design issues such as clock distribution, system level signal (such as reset or resync) distributions (to the lowest level units)...etc. For example, it would be useful to have some discussion on the via density including all hit signal vias, all required power/ground/thermal vias, as well as possible vias for system level signal distributions.

Besides power, via density, data bandwidth etc, one will need to come up with some estimate of the material budget (for different interposer design options, with realistic cooling, mechanical support etc) and see how this will compare with the existing tracker and other alternative proposals.

Clearly, the first most important step is to demonstrate the thinning and TSV technology, followed by bonding. In that sense, success from the upcoming multi-project run at Tezzaron seems to be crucial to the 3D concept at least for CMS. The first major milestone would be a working 3D stack (Short strip sensor/VICTR/Interposer/long strip sensor), followed by radiation hard 3D stack.

Due to the obvious challenges and uncertainties, it is very important to develop a clear roadmap towards the final goal: the design and construction of vertically integrated tracking layers using 3D electronics. The roadmap should include a detailed outline of the building, assembly and testing steps, the R&D needed, testing plan and check points at each step. Then for each step, clearly indicate which ones are critical (potential showstopper) and which ones that one could have a fall-back in case the one being pursued doesn't work. The 3D proposal is very bold, success is only possible with a highly disciplined and well organized approach.

Comments on testability

As clearly pointed out by the proponents in the proposal, the 3D concept involves more speculative technologies with costs and capabilities that are not yet understood. While one could argue on very general ground that this is cutting edge technology and there are still many unknowns, it is likely that ultimately, manufacturability, will be the most challenging aspect of the 3D approach for trigger upgrade. Because of that and other reasons, one has to think hard on the testability for each piece and at each step of the manufacturing process even at early stage of the R&D phase. In other words, testability should be carefully thought through and integrated in the design from the early stage of the game. This is especially important giving the fact that the design cycle is long, process expensive, with typically multiple vendors involved, with large yield uncertainty at each step for each component (esp. at early R&D phase). There is some testing capability integrated into the VICTR chip design. However, from the proposal, it is not so clear how each piece/layer can or will be tested at each stage and to what extend (e.g. interposer and sensor). Because of the 3D nature of the design, it is not even clear how to perform some of the tests for certain components, esp. before integration. It is important to develop a test methodology that can be used not only at R&D phase, but also at production phase. Related to testability is the issue with how to design for redundancy to improve the yield.