CMS Upgrade MB Response to SLHC Document:

09.06: Proposal for R&D for GaAs or GaInP Photodetectors for SLHC ECAL Endcap Calorimeters

(Contact Person: Brad Cox)

While we believe this R&D program should be initiated, there are some primary steps that should take place with results to be reviewed before the bulk of the subsequent R&D proceeds and for which funding is committed. Therefore, we provide some requested revisions. These revisions and plans for reviews, *etc*. should be made with agreement of ECAL Project Management. Please see the comments from the referees.

Specific requests for the revised proposal are:

1. Provide a plan to first study and irradiate a single channel device before investigating a prototype pixilated device. The plan should result in demonstration of robustness with respect to displacement damage by neutrons and protons as well as point defects from electron and gamma radiation by actual physical exposure and not extrapolation from lower doses. Both damage and annealing should be measured. This plan should include milestones, measurements and a review of the initial results to determine the subsequent course of the R&D program.

2. Provide more details on the number of samples to be tested at each exposure at each phase of the R&D program.

3. Provide a plan to make radiation performance measurements in situ with active readout during testing so that damage and early annealing can be measured as it occurs.

4. Provide some information on how the choice of calorimeter technology and design would affect the requirements on these photo-detectors.

5. Provide some additional information about Lightspin Technologies, *e.g*. personnel, capitalization, history and other products.

Referee #1:

This proposal is worth to be supported.

Geiger-mode APDs made of Si are currently investigated for their use in the CMS HCAL. Any preparation for the operation at SLHC luminosity would benefit from this R&D work described in the proposal – HCAL and maybe even ECAL.

GaAs and GaInP have a larger bandgap compared to Si. Geiger-mode APDs made from these materials have potentially lower dark count rates and better radiation resistance. Specially the strong increase of the dark count rate at relatively low fluence (already at 10^{11} neutrons/cm^2, Musienko NIMA (2009) in press) limits the use of Geiger-mode APDs made of Si which are otherwise very promising sensors.

As stated correctly both materials have a direct bandgap. In an avalanche breakdown are therefore many photons emitted, much more than in the indirect bandgap material SI. These photons might not cause optical crosstalk (a stochastic process which increases the excess noise factor) because of the very short absorption length (or high attenuation coefficient - not “high” absorption length as written in the proposal on p. 6) but from the shallow junction the photons can travel into the crystal attached to the diode, are reflected on the crystals wrapping material and come back to the diode where they can trigger a breakdown in another cell. This effect should be included in the R&D program. There are ways to reduce it by filters (R. Mirzoyan, PD09).

As far as I know this will be the first investigation of Geiger-mode APDs with GaAs or GaInP. The R&D is interesting by itself but might in addition open an alternative route towards operation at SLHC.

The R&D procedure described in the proposal is appropriate and defines the implicit milestones.

Referee #2:

The R&D proposal targets a very interesting technology: GaAs or GaInP photodetectors. They promise the ability to function in a strong magnetic field, and extreme radiation hardness. Although such photodetectors are at an early stage of development it is possible that development could be rapid enough to meet the needs of a "phase 2" upgrade, although the schedule would be very tight.

It is not clear with what calorimeter design the new photodetectors are intended to be used, and indeed the proposal remains deliberately non-commital on this issue. They might find a use in a number of forward or very forward calorimeter designs.

I would imagine that the relatively speculative and "unfocussed" nature of this R&D needs to be balanced against the relative modesty of the initial funding request.

I know of no other CMS work on these particular photodetectors, so the proposal does not seem to excessively duplicate work.

Referee #3:

I am not an expert on these specific devices, so this has to be borne in mind, but I have a lot of experience with radiation damage effects in silicon, InGaAs, InGaAsP, and InP materials (microstrip detectors, lasers, photodiodes mainly). We made some irradiations made to these very high levels of fluence (>10^15n/cm2) mentioned here for applications inside Tracker and pixels. Such high fluences normally provoked massive damage in the devices. Use of high fluences also led to difficulties in handling the irradiated parts after the test, since they became too radioactive to collect shortly after irradiation, and even up to a year later it was not possible to ship them as 'excepted packages' but this is a strong function of the materials used in the packaging/mounting of the samples. This point about activation affects also any possible testing by institutes without radiation safety protocols in place (eg at the suppliers, if their input is needed post-irradiation).

The proposal here to make a detailed radiation hardness evaluation is a very important early step before going much further with these devices. I am very sceptical about presuming radiation hardness from fundamental material properties such as bandgap. Defects and impurities introduced during processing are often very important in determining the actual radiation hardness, given that these introduce states into the bandgap which, combined with the radiation induced defects that also introduce states into the bandgap, can be very damaging. It should be noted that GaAs was for a long time expected to be much more rad-hard than silicon for Tracker detectors and yet it was finally dropped since it did not prove to be the case at higher fluences.

I would strongly recommend to give equal, if not higher priority to displacement damage tests (and subsequent accelerated annealing, if there is annealing) with fast neutrons and protons, rather than the current emphasis upon testing with electrons sources. It is a fact that the nature of radiation induced defects generated by electrons is fundamentally different to those generated by neutrons, since the stronger recoil of atoms and nuclei from incident neutrons or protons cause "defect clusters" to form, in contrast with a more uniformly accumulated distribution of point defects from electron (and particularly gamma irradiation).

To exclude (or examine if any) effects of ionization damage, I recommend to make some simple exposures with a Co-60 gamma source to a high dose and check for effects before/after.

It does not appear to be the case here, but I would like to make the point anyway, that the radiation tests should avoid any extrapolation to expected final conditions (besides taking into account the flux and time of exposure when there is annealing observed) and should instead plan to exceed final fluences by some reasonable safety factor, which can be used to provide a greater degree of confidence in the eventual radiation hardness.

It is often of great benefit, especially when working with a limited number of samples, to plan to measure radiation effects (and early annealing) in-situ with an appropriate test system. It was not completely clear whether the test system will be installed inside the radiation source. With hadron tests this is often inconvenient due to damage or activation of the test-setup and maybe it would be useful to consider using optical fibres to deliver reference light signals to the detectors under test.

The number of samples is not given. Of course more is better, allowing some variation within tests, and some control samples for reference. A useful number in past experience was ~3-5 devices (per wafer) per test procedure and preferable more, allowing some margin for failures and variations in conditions applied (bias/unbiased, and accelerated annealing at different temperatures). It is often worth investigating the effect of biass as well as the sample temperature during irradiation and annealing (particularly if this is not the same as in the final application), since these factors can change significantly the annealing rate and therefore the amount of damage observed in a test that takes a significant length of time.

Referee #4:

This proposal aims at testing GaAs avalanche photodiode arrays for functionality and radiation hardness. Its goal (testing GaAs APD arrays) can be reasonably achieved in one year given the resources indicated. The real question however is: will these tests take CMS closer to the development of a radiation hard photodetector for SLHC EE? To the best of my (limited) knowledge, GaAs has in the past shown most of the time inferior resistance to radiation than Si, be it for sensor or for photodetector applications. This is usually attributed to the poorer crystal quality of compound semiconductors and less mature processing techniques. Will this conclusion be different for avalanche structures? Have material and processing quality improved as the authors suggest? Answering these questions might justify a time-limited study, but in that case why couple it with the investigation of a PROTOTYPE pixilated chip? In a first step, the study and irradiation of a single channel device might make more scientific and economical sense. It would allow the experiment to start from a relatively well understood structure at a much lower initial cost, and would eliminate the risk of complex device effects masking the intrinsic behaviour of the APD. In case of promising results, one could in a second step move to a more complex array structure.

Concerning the industrial partner LightSpin Technologies Inc. I failed to find a connected web site (which may only have been bad luck), and found different postal addresses and different operating names (such as polychip). It might be reassuring to document a bit better the experience and robustness of this company.

In summary, I find this proposal marginally appropriate for the needs of CMS at SLHC. It has in my opinion a too high initial cost/potential ratio.