TRACKER-WIDE REVIEW:

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Comments to draft:

"Selection of the silicon sensor thickness for the Phase-2 upgrade of the CMS Outer Tracker"

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The paper presents a comparative study of two strip sensors candidates for the phase II upgrade of the CMS OT. It investigates experimentally the performance of silicon strip sensors of the CMS-OT design for the HL-LHC for the fluences expected for the HL-LHC. A comparison between the baseline thickness of 290 μm and the option thinned down to 240 μm is performed. It is found that both have quite similar performances with respect to the charge of seed signal, hit efficiency and noise occupancy. The performance of the 290 μm sensors appears to be somewhat superior, and together with other criteria, like cost and ease of handling have driven the decision by CMS to choose 290 μm for the OT-sensor thickness.

General comments:

- Some performance parameters as the charge of seed signal, hit efficiency and noise occupancy are presented but some other important ones, like position resolution, two particle separation and stable operation are not mentioned at all in the draft. They also depend on the sensor thickness. They should certainly be at least mentioned, and possibly discussed in the paper. After all, the resolution is one of the main reasons for using silicon strips.

A. Comments about English/Style/Formatting:

General comments:

- SI units should be used: n_{eq} is not a unit. The n_{eq} should be part of Φ, e.g. Φ_{eq}. In the paper Φ and later F are used for fluence.
- Using different units is quite confusing: **Fig.8** pA/mm^3, **Fig.9** mA/cm^3, **Fig.10** μA -> please unify.

Abstract:

- Please add also the thickness of the thinned sensors.
- "sensors with about 300 μm thickness will survive even the highest considered fluence" this is slang, as "survive" is unclear.

1. Introduction:

- **l.2:** "provide an instantaneous luminosity of up to... for about ten years" --> means permanent running without interruption.
- **l.11:** "… tracker could survive" --> again, survive is a bit vague.
- **l.22:** "records bits as binary 1" --> this is a strange formulation, which is also not needed.
- **l.37:** "the radiation-induced defects in the silicon substrate are essentially unchanged with time." --> meaning not clear.
- **l.55:** "made of FZ ..." --> the acronym should be moved here from l.82.
- **l.64:** "how the optimal thickness was selected" --> optimal remands to an optimization process, maybe is better: "how the thickness was selected between the two options." or similar.

2. Samples:

- **l.73-78:** "strip" is first used for the implanted and later for the Al strips.
- **Table 1:** Quote in a table pitch and strip length of all sensors.
- **l.87:** As HPK is not the crystal producer, HPK material may be confusing: HPK buys the material at a producer, but other companies can also buy oxygenated FZ material.

3. Radiation environment and irradiation procedure:

- **l.102:** "The fluence is split into different particle types" --> poor language, please rephrase.
- **Figure 4:** Neutrons (blue curve) should be drawn also for r > 20 cm. Please use an updated version of this plot.
- **l.112:** "Previous studies have shown that oxygen-rich silicon material exhibits different properties when exposed to charged particles than when exposed to neutral particles" --> it is difficult to be understood: the difference in radiation damage for different particle types, which is not properly accounted for by the NIEL hypothesis is a general feature, and not limited to oxygen-rich material, please rephrase.
- **Table 5:** An estimated uncertainty of the irradiation fluences would be helpful.
- **l.129:** Consider also removing the sentence. This was already stated above.

4. Measurement procedures:

- **l.179:** "The sensors are mounted on a PCB, which is fixed to a cooled copper block, for biasing." -> not clear, please rephrase.
- **l.190:** V was voltage before and is now the volume.
- **l.250:** "window of $\pm$ 45 μm -> not clear, please rephrase.
- **Footnote p.13:** "firing channels per triggered event." -> this is too colloquial slang, please rephrase.

5. Results of the sensor characterization:

- **l.259:** "the shapes of the IV curves are very uniform" -> poor formulation; do you refer to the spread for sensors of the same type.
- **l.280:** "pure neutron irradiation" -> poor wording, please rephrase.
- **Table 10:** several numbers in italic.

6. Results of the charge collection study:

- **l.374 (also 309):** "In conclusion" --> this can be made more evident, maybe bold. The discussion above is very lengthy and the reader may want to skip to the conclusion. Please try to shorten and focus the discussion.
- **Table 12:** Should be removed or reduced to 3 columns only. This is not necessary to present s, s*4 and s*12.
- **Figures 15 and 16:** Do the thicknesses of the red bands have a meaning? If not please change them with "standard" lines.

7. Beam test results:

- **Figure 18:** Yellow is not visible.
- **Figures 18 and 19:** F_{tot} and F are used for Fluence. Usually Φ is preferred. Since n_{eq} is not a SI unit, it is preferable to quote Φ_{eq} = XX cm^{-2}

8. Further considerations:

- **Table 13:** "Relative difference" is the only part in italic.

Acknowledgements:

- **l468:** "TThe tracker group" --> "The tracker group".

B. Everything else (e.g. strategy, paper structure, emphasis, additions/subtractions, etc):

Abstract:

- "… could potentially deteriorate" --> it will certainly deteriorate, it is merely a question if the deteriorated performance is still acceptable.
- It is not clear here if 1.5 x 10^{15} is just the limit of this study or the maximum expected fluence.

1. Introduction:

- **l.7:** "… macro-pixel sensors" --> add a sentence explaining what they are.
- **l12:** Please provide a number for the pileup.
- **l.13:** "finer granularity" Is it correct that the increased pile-up results in a significant increase in multiple hits in strips with an area of the present OT?
- **l.13:** "… tracking information at the Level-1" --> maybe one can briefly introduce pt modules here.
- **l.36:** "The operating voltage can be …" --> Are 600 V used from the beginning for all layers?

2. Samples:

- A short description of the biasing scheme would be helpful. How does the 1.5 MΩ bias resistors influence the C-V measurements of the sensor?
- **Table 2:** Has the distance sensitive area to cut edge been specified? --> it should be given. Are the depths of the strip and p-stop dopings known? It is the integral which is relevant.

3. Radiation environment and irradiation procedure:

- **l.137 & further text:** which irradiation was done first? If KAZ first then at TRIGA you have high annealing.

4. Measurement procedures:

- **Table 6:** What is the backside voltage in these measurements? Was the guard ring grounded? Is this considered when calculating the active volume?
- **l.190-191:** The definition of α is not the one given in Moll thesis and subsequent papers. In the original definition of α the difference of current irrad-current before irradiation is used and α is defined for a voltage above full depletion. At which voltage is the current calculated?
- **l.199:** The seed signal distribution depends on the charge sharing, which depends on the Lorentz and the track angle. The angular distribution of the tracks from the source and the deposited energy is not presented in the paper, and as the geometry of the beta setup is not given, cannot be estimate either. Thus, one can have serious doubts that the results with respect to the efficiency of the source measurements can be trusted. As they seem to indicate that the situation is quite marginal, more information would be needed to have confidence in the results for the sensors exposed to the highest fluence.
- **l.202 & further text:** The authors refer to "signal height". Amplitude is more appropriate than height if a voltage is measured. Is the signal amplitude or charge measured? i.e. is there a charge amplifier in the readout system? For the source tests, the measured charge distribution has been fitted by a Landau distribution convolved with a Gaussian and the performance criterium is derived from the MPV of the Landau distribution. It should be stated what distribution has been used, as different authors use different distributions with the name of "Landau". Why the seed distribution, which is influenced by charge sharing should follow a Landau distribution?

In addition, **Fig. 9** shows that the MPV of the Landau distribution does not characterize the measured charge: It strongly depends on the sigma of the Gaussian, and the MPV Landau is at 11 ke, whereas the MPV of the data at 13 ke. Thus, the sentence **l.205** "the resulting MPV seed serves as a good estimator of the seed signal strength to compare the performance of the two materials under the different conditions." needs to be demonstrated. (e.g. dependence on the angle for different sensor thicknesses, effects of Lorentz angle, dependence on noise). Along the same line: Has the relation that $MPV_{seed} = 12\ \sigma_{noise}$ corresponds to 99.5% hit efficiency been demonstrated? Is the basis of this rule introduced by the CMS Outer Tracker Sensor Working Group documented? As it is central to what follows, this has to be explained and referenced.

- **Figure 6:** It appears from Fig. 6 that the MPV quoted is the MPV of the Landau and not that of the function describing the data. Due to the very strong correlation between Gaussian and Landau widths, the value of the MPV of the Landau cannot be determined precisely. For calibration purposes it also does not have real meaning as it refers to the ideal physics of charge deposited by a MIP and not to the observed one due to instrumental effects. The MPV of the convolution is preferable for the discussion in this paper.
- **l.243:** A definition of the efficiency as calculated after the cuts should be provided.
- **Figure 8:** Are the shapes of the IV curves understood? E.g. the step at low voltages. The two brown colors can hardly be distinguished. The shapes are very different to the expectation for the bulk current. For all I measurements, T should be given (e.g. also **Fig.9**). Are the IV curves for the sensors thFZ and FZ comparable? Here two aspects are mixed: a difference in absolute thickness of the active area and the difference due to active-physical thickness. The IV curves after irradiation should be shown. How is the behavior of the current between 400 - 600 V? does it saturate?

5. Results of the sensor characterization:

- **l.257:** It would be interesting to see the CV measurements and the definition of full depletion voltage and thickness. Can you document these values in table 9? What is the thickness used for the volume normalization of FZ290?
- **l.261:** What are the "thinned mini-sensors" with respect to "thin sensors" on line 257? Please use the names to refer to the sensors. The thinned mini sensors have a higher leakage current … than what? To confirm the suspicion that the higher current comes from the thinning process, one should instead compare 240 μm thinned to 240 μm not thinned. To avoid the difference introduced by the thickness. These sensors are available to the collaboration: a sensor of 320 μm thick and an active thickness of 290 μm was also characterized in previous studies and was reported to have the highest signal in Ref. 4. It is not clear why the active thickness of 290 μm became the baseline material, and why sensors with the same active thickness are not directly compared to access directly the effect of thinning.
- **Table 9:** The values for thFZ290 and FZ240 options should be added as well. Otherwise, the interpretation is not clear. What causes the increase of leakage? The thinning process or the nosier 240 productions? Please, add the full depletion voltage.
- **Figure 9:** The comparison to the α literature value is misleading. Is the α comparison with literature at the same T, V and annealing? The expectation from the literature is for a voltage above full depletion. **Fig. 10** should be shown first. It shows no sign of full depletion for the FZ290 and a strange increase above 400 V for thFZ240. It is arbitrary to choose a voltage and quote an "α" parameter at that voltage. This quantity cannot be compared to literature. One can plot α versus bias voltage and see it is continuously increasing. It is always possible to find a voltage value for which α agrees with the literature. α is not a constant in this case as full depletion is not reached, or other effects kick in. This is a wrong interpretation of the data (stated also in **l.273**).
- **l.282-284:** How is the so-called "equivalence" calculated? Document the true annealing steps in a table and an explanation of the conversion. In general, the real condition could be quoted in the measurements and the interpretation could be left to the discussion.
- **Figure 11:** Please quote always (also in other places and figures) the experimental true annealing step.
- **Figure 14:** This figure should be removed. α is voltage dependent. Most likely during operation the voltage will be adjusted using some criteria, depending on the fluence. This is not the relevant parameter to quote for operation. More interesting is the reduction of the current itself with annealing, for few reference bias voltages.

6. Results of the charge collection study:

- **l.323:** "MPV seed should be three times larger than the threshold" --> How do you come to this conclusion? What is the observable used to fix this value? What is suggested here is a S/threshold > 3. It should be motivated by showing the cumulative distribution and indicating where the threshold cuts 0.5% of the events below the MPV, to obtain an efficiency of 99.5%
  Note: The definition of MPV must be changed to be the peak max of the convolution function first.
  Note: These calculations are performed for vertical incidence, i.e. for the largest seed signal. The seed signal will be much smaller for inclined tracks.
- **Figure 15:** The behaviour of the point at 0 annealing days for the FZ290 should be commented.
- **Figure 17:** The results presented here are pessimistic given the wrong choice of the observable (MPV_{Landau}) and on the other hand they are only valid for vertical incidence. A discussion should be added.

7. Beam test results:

- The beam test data confirm that the signal for irradiations to 5E14 cm^{-2} is marginal for 99.5 % efficiency for both sensor thicknesses. The data are at 0° without a magnetic field, which gives the least charge sharing and therefore higher seed signals, than for the situation in the magnetic field and tracks at an angle. --> some comments on this should be made in the paper, and a study, which goes beyond this paper should be initiated. Measurements at different angles are no problems in the DESY setup used for the 0° measurements and probably the easiest way to answer these questions.

9. Conclusion:

- **l.495:** The last statement appears a bit in contradiction with the previous part. Please be more specific (also repeating if needed a summary of the results).