Dear Ulrich,

Thank you for your comments. Most of them have been implemented or noted (see revised version of the paper) and detailed answers are added below.

General comments:

- Generally the paper reads very well, there are no significant language issues.
- What is the group of readers this paper is targeted to? In my opinion this should be a physicist interested in HEP instrumentation in general, not necessarily from the LHC. Most sections are ok for this target group, but some are written for specialists only and need much more explanation to be accessible.
- There is some imbalance in the depth in which topics are treated. For example, the module assembly is dealt with on 1 page (despite several assembly and test procedures that have been developed, different bump bonding techniques, ...) On the other hand, each test procedure is described in gory details.
- At least in my group, a lot of details that go beyond this paper are documented in PhD (and master) theses. We should make these resources available by citing them wherever appropriate.

Line-by-line comments:

- Abstract:
  - Start with more context: The original silicon pixel detector of the CMS experiment at the CERN Large Hadron Collider has been replaced...

    → added first sentence following Katja's suggestion: The CMS detector at the CERN LHC features as its innermost subdetector a silicon pixel detector.

  - Use consistent naming for the upgraded detector. In the abstract there are two already, "upgraded CMS pixel detector" and "CMS Phase-1 pixel detector" (where Phase-1 has not been defined before) → ok, Phase-1 introduced in abstract
- Chapter 1:
  - L2: at the CERN Large Hadron Collider (LHC) → ok

    - L3: Suggest to reorder these sentences: The pixel detector is a key component of the CMS experiment and is indispensable for high-precision charged-particle tracking close to the interaction point and for vertex reconstruction. The pixel detector is located in a particularly harsh radiation environment characterized by a high track density. → ok
    - L13: the phrase "pixel Phase-1 upgrade" refers to the upgrade `process`, not to the upgraded system. Suggest to just call it "upgraded pixel detector" and "upgraded pixel detector system" if also the services are addressed" → ok, but still introducing Phase-1 here.
    - The new geometry has not been explained yet, better start like "The radial distance to the interaction point of the innermost sensitive layer has been moved closer to the IA point ...; therefore, faster FE electronics had to be developed... → ok
    - L27: In this paper, the design... is reviewed and its performance ... is presented. (a paper cannot do anything actively) → ok.
    - L34: Reference to chapter 9 (nuclear interactions) missing → yes, added.
- Chapter 2:
    - L38: upgraded pixel system → ok
    - L41: to have four-hit coverage → ok
    - L43: suggest to also mention redundancy from fourth layer → ok
    - L45: give number of pixels per sensor module, e.g.: Each module consists of a sensor with 16\times4160 pixels with a nominal size of ... → ok
    - L49: upgraded pixel detector system → ok
    - L51: supporting eight detector modules → ok
    - L56: upgraded pixel detector system → ok
    - Table 1: add header row for BPIX: Layer | Radius | Number of ladders | Number of modules → ok
    - Fig. 1: upgraded pixel detector → ok
    - L64: suggest to introduce jargon word "services" here (why do you mentioned power cables and fibers separately, are they not part of the services?) → ok
    - L65: upgraded pixel detector has 1.9 times ... than the original pixel detector → ok
    - L67: The upgraded pixel detector system → ok
    - L69: readout and power systems (plural) → ok

- L79: why do you only mention ionizing radiation, but not NIEL fluence (which is very relevant for the sensors)? → right. Added table with fluence.
- L81: The upgraded pixel detector maintains... and overcomes limitations of the original pixel detector at higher luminosities. → ok

- Chapter 3:
  - L84: remove → ok
  - L85: upgraded pixel detector → ok
  - L87: array of 2x8 →ok
  - L94: "upgrade modules" sound strange, maybe: upgraded (pixel) detector modules? → ok
  - L102: this section is very difficult to understand for non-experts on silicon sensors, see detailed comments below
    - L105: suggest to delete: as described... → ok
    - L106: pixels along the chip boundaries have twice the area and those at the corners have four times the area compared to a standard pixel... → ok
    - L108: explain n-in-in, e.g.: follow the n-in-n approach, with strongly n-doped (n+) pixelated implants on an n-doped silicon bulk and a p-doped backside. In a reverse-bias configuration, the n+ implants collect electrons, which is advantageous as their mobility is higher compared to holes. → ok
    - L110: need mini-introduction to radiation damage to understand "trapping" (plus point to 3.1.4?), e.g.: The charge collection in a silicon sensor is impeded by radiation damage: charge carriers may be trapped for a certain time such that they do not contribute to the charge signal. Another advantage of collecting electrons is that they are less prone to charge trapping than holes. → ok
    - L116: "requires a double sided sensor process" is obscure for non-specialists, maybe: requires that photolithography processes must be applied to both sides of the sensors (double-sided process)→ ok
    - L118: the concept of guard rings may also not be familiar to the reader, please add a small explanation → ok
    - L120: "an n-side isolation" is difficult for non-specialists, suggest to explain that electron accumulation below the Si oxide layer that would

short-circuit the pixels and that therefore the pixels must be isolated from each other. → ok

- L129: The small gaps ... also facilitate the implementation of punch through bias structures, the bias dots. → ok
- L130: Suggest to break this massive pile of information down in smaller pieces, e.g.: The bias dots provide a highly resistive connection to each pixel. This can be used to apply bias voltage to the sensor prior to any further processing. This in turn allows sensor quality assurance measurements, such as the current-voltage (IV) characteristic. → ok
- L133: explain FZ, e.g.: wafers from silicon monocrystals produced in the float-zone (FZ) process. → ok
- Fig. 5: More information in caption, e.g.: Photographs of four pixel cells on a BPIX sensor (a) and on an FPIX sensor (b)→ ok
- L141: reverse bias voltage. → ok
- L142: the FPIX sensor subsection is much shorter than its BPIX counterpart. Suggest to extend to give the same level of detail. B.t.w.: why did you avoid the names of the sensor manufacturers? → FPIX section is expanded and vendor names have been added for both BPIX and FPIX
- L154: wouldn't it be more natural to argue with the band model rather than the E field when talking about radiation damage? → to be discussed
- L156: is available within the 25-ns bunch crossing rate of the LHC → not sure what this comment refers to
- L157: suggest to mention that the threshold of the readout is due to noise → cross talk is more important than noise. The sentence has been rephrased, but the discussion of the readout threshold seems more appropriate in later sections.
- L160: This fluence corresponds to → ok
- L161: Has the signal height been measured before and/or after radiation? Please add this information. → both, added.
- Fig. 6: the quality of the plot seems not adequate for a paper in 2019 (too small axis titles, no units in legend), suggest to "beautify" and then refer to it as "after [5]" → will be removed
- Fig. 6 caption: chemical element not in italics → ok
- L164: full depletion of what? → rephrased.
- L165: A higher bias voltage was not... → ok
- L166: Motivate why 10000 electrons are sufficient, e.g. by moving the information from L170 earlier → will be removed and refered to results from operation

- L172: During the second long shutdown of the LHC (LS2) →ok
- L175: spatial resolution → ok
- L180: "significantly higher flux" compared to what? → other layers added.
- L182: higher than a few tens → ok
- L189: and in FPIX → ok
- L191: suggest to add a reference to the column drain mechanism → ok, added R. Horisberger, „Readout architectures for pixel detectors“, Nucl. Inst. Meth A 465 (2001) 148-152.
- L213: "a counter running behind" sounds strange to me, maybe: a counter delay with respect to the bunch crossing counter... → ok
- L215: this is the first time the readout token is mentioned. Suggest to introduce TBM and its role briefly in the beginning of Section 3.2 → Function of the TBM is introduced on L91. Here added „readout token issued by the TBM“
- L223: spell out acronym ADC the first time you use it → ok
- L224: spell out acronym FIFO the first time you use it → ok
- L225: spell out acronym PLL the first time you use it→ ok
- L227: cross talk between what? → added „between pixels“
- L227: time walk of what? → of the signal
- L228: below 1800 e^- → ok
- L233: shows excellent performance → ok
- L238: data losses ... outer BPIX layer are less → ok
- L241: faster compared to what? → compared to PSI46dig. Not sure if it is needed to add this explicitly
- L258: could be mitigated (conditional) or were mitigated (past tense)? → changed to were
- L272: a reset signal (to whom?) → ok, to double-column
- L273: "found and fixed" is jargon, maybe: identified and corrected → ok
- L278: does the time-walk optimization also refer to the revised version of the PROC600? → yes, added explicitly.
- L280: cross talk between what? → added „between pixels“
- Fig. 8: unit on x axis should be cm^2 (superscript missing) → yes. Noted. To be done.
- L282: First state what the TBM actually does, before going into the details and comparing it to the old version → ok, added.

- L292: "same header and trailer timing" remains obscure for non-experts, please explain better → has been rephrased.
- L297: what is meant by "trigger stack" in this context? → added explanation of stack.
- L299: N in math mode → ok
- L306: what is the TBM stack? Is it the same as the "trigger stack"? → should be clear now.
- L313: has there been an outline of the LS2 consolidation work before in this paper? → no. Now added in the introduction.
- L321: four readout links → ok
- L330: I believe it would be of great interest to the read to expand a bit on bare module production: reasons for multiple BB vendors, new BB processes developed at DESY (solder-ball jetting) and KIT, bare module probe stations, differences between indium, AgSn, SnPb, different UBMs, cleaning procedures, quality control, ...) → this would expand this section by a lot. Propose to give a brief description and add references for details.
- L354: the µ should be in upright, suggest to use siunitx package. → ok. Use CMS pdefs.tex
- L354: the cap was made of Kapton = polyimide, not polyamide → ok
- L358: the section on FPIX module construction is strangely different from BPIX, with details a places where I would find them irrelevant. The two sections should be made similar in the level of (relevant) detail, examples:
  - L365: if you give details on the encapsulant, please give the type. Alos, Sylgard is a trademark. → Sylgard defines type, trademark kept
  - L366: LabView is a trademark → rephrased
  - L369: the "primary issues" mentioned here seem a strange choice. Of course, excess glue is something each production center faced at some point. At least at KIT the reason for this was found and eliminated during preproduction. → issues for FPIX removed

Comments: Some more details are now provided in BPIX section, some details have been removed from FPIX section. To be reviewed if further measures are needed.

- L383: the section suggests that module testing has only performed once after production. On the contrary, key to

high-quality modules was to test as early as possible. Therefore part of the tests have been performed first on bare modules. → This is of course true. But the title of the section is „Module qualification and grading“ and thus only discusses the tests on the final modules. The fact that test have also been made during bare module production is stated in section 3.4

- L384: A suite of tests was performed → ok
- L388: damage (singular, mass noun) → ok
- L389: pXar is specific to the community. Is the name really relevant? If yes, is there a reference (e.g. anything from Urs Langenegger or Simon Spannagel's PhD thesis)? → added reference to Simon's thesis
- Fig. 11: plot as it comes out of the box, to be made more pretty → figure has been removed.
- L408: If the number of signals sent to the pixel and the number of signals read out from the pixel is the same. → ok
- L429: suggest to add erf parameterization to introduce threshold and noise parameters → ok
- L447: the BB test was much more subtle than is conveyed here. The capacitance of the device depends critically on the bump height, which was much smaller for indium than for solder bumps. This was especially important during bare module probing. → indeed reality is more complicated, but what is said in the text is correct. Prefer to not go in more detail.
- L460: that there is no hidden sensor damage (mass noun) that manifests itself → ok
- Fig. 12: need unified plot style. Add legend to upper plots. Is there a Gaussian fit involved for the upper plots? If so, explain in the caption. → noted. To be done. Fit numbers to be removed.
- L476: metallic films or foils or plates? → foils.
- L477: you mean the material (or more precisely: chemical element) of the foil, right? → yes, changed.
- Fig. 14: x axis title should be: Hit rate [MHz/cm^2] → noted, to be done.
- Fig. 15: x axis title: pulse height → noted, to be done.
- Fig. 15: "Calibration … in electrons" sounds strange to me, maybe: Clibration of one ROC on a pixel detector module with characteristic X-rays. The pulse height in units of the internal calibration signal V_cal shows a linear dependence on the number of electrons expected to be collected from

different target materials. From a straight-line fit to the data points, a calibration constant of ??? e^-/V_cal is extracted. →ok
    - (Either label the points in the plots or add to the caption which data point is which material) → ok
    - L486: good timing settings found? → ok
    - L492: if I remember correctly, the ratio of leakage currents at 100 V and 150 V was part of the criteria → This criteria was only used to discriminate Grade A and B modules. At +17C, a ratio of I(-150V)/I(-100V) <=2 would be Grade A, >2 Grade B. Since we do not make a difference between Grade A and B in the text, this criteria is not mentioned.
    - L494: add white space between 1088 and (96) → ok
    - L499: The number of produced BPIX modules over time is presented… → ok
    - L503: damage (mass noun) → ok
    - Fig. 16: redo plots in same style, label the dashed line in upper plot, add a similar line in lower plot → noted, to be done.
    - Fig. 16 caption: this just shows the number of modules vs. time, not the yield (= percentage of detector-grade modules) → noted, to be done.
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- Chapter 4:
    - L529: spell out acronym CCU? → ok
    - L530: spell out acronym PIA? → ok
    - L547: explain meaning of "balanced" in this context → DC balanced
    - L556: different implementations of what? → of the services.
    - L564: four humidity sensors → ok
    - L566: stack of three connector boards → ok
    - L571: two DOHs → ok
    - L573: electrical signals → ok
    - L573: Kapton (trademark!) → polyimide → ok
    - Fig. 18: will the updated drawing contain labels? → yes. To be done.
    - L581: seven → ok
    - L582: seven → ok
    - L583: four → ok
    - Fig. 19: add labels to drawing → ok, done
    - L622: "The regulation, i.e. the delivery..." sounds strange. If you need the term "regulation" later on: The delivery of the output voltage, called (voltage) regulation, ... → ok

- L628: passives → passive components → ok
- Fig. 21: add labels to photographs? → should be clear from caption
- L714: Delete "At the time of writing..." (Run 2 already over) → ok
- L716: eliminate the leakage current problem? → yes.
- L720: CO2 cooling as the technology → ok
- L726: two-phase accumulator → ok
- Fig. 22: drawing to small, suggest to move phase diagram below cooling system sketch. → ok, done
- Fig. 22 caption: add short description of `what` is shown in the drawing and diagram → ok.
- L744: this may be a matter of taste, but I would prefer the requirements (w/o the paragraph on redundancy) before the cooling concept → changed title
- L759: To ensure continuous operation → ok
- Fig. 23: labels too small → not sure how to improve.
- Fig. 24: labels too small → figure has been removed.
- L772: backup → ok
- L773: eight cooling loops → ok
- L784: backup → ok
- Fig. 25: these screen shots are not very instructive for non-experts. They are also too small for anything to be read off the plots.
- Fig. 25 caption: describe what is shown on the plots are these time series of temperature readings?
- Fig. 25 caption: Performance of (mass noun) → figure has been removed.
- Fig. 27: The measurements are → ok

- Chapter 5:
  - L826: half shell underwent → ok
  - L849: use math mode for variable z → ok
  - L857: this chapter has some redundancy with Section 4.3. Refer to that chapter rather than repeating. → ok, removed first sentences.
  - L864: are joined with → ok
  - L869: use math mode for variable z → ok
  - Fig. 29: label Segments A, B, C on photograph → ok, added.
  - L873: use math mode for variable z → ok
  - L876: is VCR the Swagelok trademark or the acronym for something? In either case, indicate what it is. → it is a trademark, kept.
  - Fig. 30: labels way too small → noted. To be removed.

- L919: "identical to Phase 0" is not very useful if you do not know that design. Add a reference? → removed statement.
- Footnote 4: Dow Corning → ok
- L939: Cooling lines → ok
- L939: This section only describes the cooling supply/return, but not how the cooling is distributed inside the disks (only in 5.2.6). Suggest to at least add a hint here. → This is explained in the disk section on L908ff.
- L953: Kapton → polyimide → ok
- Fig. 33: indicate where the test heaters are located that you mention in the caption → to be followed up.
- L974: why has the radiation hardness only been tested using gammas and not protons and/or neutrons? → this part has been removed
- Fig. 34: all labels way too small → figure has been removed.

- Chapter 6:
  - L993: access to what? To the CMS detector.
  - L1029: "could be" (conditional) or "were" (past tense)? → changed to were
  - L1045: In this paragraph you are mixing present tense and past tense inconsistently. Things that happened once should be in past tense → has been improved.
  - L1053: delete "neatly" → ok
  - L1064: can "thermal cycle" really be used as a verb? → rephrased
  - L1072: inside CMS → into a fixed position inside CMS? → ok
  - L1076: joined → ok
  - L1086: comma after 2017 → ok
  - L1089: "operating the detector cold" is jargon, maybe: operating the detector at -20C (cold test). → ok
  - L1092: leading to short circuits → ok
  - L1095: detector was ready for installation → ok
  - L1109: High quality modules is not well defined here → is removed
  - L1112: addresses → ok
  - L1112: flex cables → ok
  - L1122: why "having ... installed"? →changed.
  - L1135: flex cable → ok
  - L1146: up to the point where a test? → ok
  - L1147: I am surprised that the problem with abrupt cool-down was only found on the half cylinder and not during previous power cycles. Can you motivate this better

(different cycle frequency?) → has been rephrased: „For the first half cylinder tested, 0.153\% of pixels were lost in patterns at the corners of modules that were thought to be due to cable strain, uneven pressure when screwing in a module support, and/or issues due the the number and nature of temperature cycles done: CO$_2$ gas was allowed to enter the detector until the temperature of the half cylinder under test plateaued to within about 10-15C of the set point of the coolant at wich point the CO$_2$ liquid was allowed to flow into the detector. In order to reduce possible temperature effects for the second half cylinder tested, we limited the number of temperature cycles by leaving the detector on and cooled, and we modified the CO$_2$ system to provide coolant at an adjustable temperature in 5C steps. For this second half cylinder, we found 0.024\% of pixels were lost in patterns at the corners of modules. For operations at CERN, the CO2 system was more adjustable and we limited the cooldown rate to 1C/min or less. We did not notice an increase in bump bond loss after reassembly and testing at CERN.“
    - L1168: delete "in any case" → ok
    - L1180: where joined → ok
    - L1181: out of the transport box directly into the final position? → rephrased.
- Chapter 7:
    - L1258: I would start this section by pointing back to the module tests described in Chapter 3. → This is now done in Section 7.4 since it does not apply to the previous subchapters.
    - L1259: "Pixel thresholds are..." starts too quickly. Maybe "The lowest possible value that can be chosen for the detection threshold of a given pixel is an important performance parameter..." → ok
    - L1278: The thresholds for L1 → ok
    - L1281: threshold and noise values per ROC → ok
    - Fig. 44: use the same abbreviation of "layer" as in the rest of the text, e.g. L1 or Layer 1 → noted. To be done.
    - Fig. 44: x axis label should not only show units but the quantity that is plotted (left: threshold (electrons), right: noise (electrons)) → noted. To be done.
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- Chapter 8:

- L1311: "a few additional calibrations" sounds too colloquial to me → removed a few
- L1313: The alignment of the pixel detector deserves more than just five lines! Suggest to add a section to Chapter 7 (and call that chapter "Calibration and Alignment") following the following conference proceedings article: https://www.sciencedirect.com/science/article/pii/S0168900218305953?via%3Dihub → The description of the alignment will be part of the Run 2 tracking performace paper that is being planned. Therefore it is kept short here. Nonetheless, the paragraph has been improved and proper references have been added.
- L1320: Suggest to put material on the number of working channels as a separate section → ok
- Fig. 45: The distributions for L1 → ok
- L1327: fixed is too colloquial → repaired, solved, corrected ... → ok
- L1357: comma after 46, →ok
- L1357: plateaus → ok
- L1357: Fig. 46 does also show the plateaus for L3 and L4 → ok added
- L1384: link this section to the section on the DC-DC crisis → ok
- L1395: remind reader that 2019/2020 is LS 2 and will lead to Run 3 → ok
- L1409: the definition of "in-time threshold" is not very exact. It's not the `increase` in threshold, but rather the `sum` the threshold and the time walk. → rephrased
- L1414: fixed → corrected → ok
- Fig. 47: align plots and consider choosing the same x and y axis ranges for both → plots to be merged. Noted.
- L1425: pixel charge → charge collected in a single pixel → ok
- L1436: suggest to move explanation of charge trapping in the sensor from L1437 up here. → ok
- L1440: "production depth" is not well defined here, do you mean sth. like the distance from the sensor surface (or implants) at which the charge has been produced in the substrate? Please define. → from the sensor surface. Added.
- Fig. 48 caption: explain that the curves have been fit with a Landau (+Gauss?) and that the most probable value (MPV) is given for each layer/disk → ok, MPV to be removed from plots.

- Fig. 49 caption: mention that the profiles are for different years of data taking, different HV settings, and different annealing times → ok
- Fig. 50: spell out luminosity in x axis title → plot to be replaced. Noted.
- L1469: More meaningful title? Performance of what? → suggestions welcome. Changed to detector performance
- L1484: that is → which in turn depends on
- L1504: Gaussian or a t-student function → Gaussian or a Student's t distribution → ok
- L1507: radial position of the layer → ok
- L1509: amount of radiation is too unspecific. Do you refer to total dose or fluence? → fluence. Rephrased.
- L1519: do you really want to explain radiation damage with electric fields only? Usually one would go back to mechanisms that change the effective doping concentration. → Ok, replace by
- "With irradiation the effective doping of the sensor material changes which modifies the electric field and lowers the charge collection efficiency."
- Table 2 caption: in volts → ok
- Table 2: The table style is rather ugly, but I do not have a great alternative idea to fit all this information in a single table → style can be improved. Suggestions welcome.
- L1544: in Figs. 53 and 54 → ok
- L1549: "used by CMS pixel can deal..." sounds too colloquial, how about: used in the CMS pixel detector are designed to cope with these signals → has been rephrased
- Fig. 55: all labels way too tiny → noted. To be done.

L1551: this section should close the loop to the thermal mockup in 4.3.5. If there is no other public write-up of the results, suggest to refer to Julia Hunt's Master thesis (https://ekp-invenio.physik.uni-karlsruhe.de/record/49071) → added sentnence after line 1565-1566 "The distribution of temperatures have been studied usin gthe thermal mockup (see 4.3.5), nevertheless the exact value if the temperatures within sensors are only known with the 1 - 2 dgree range [Ref julia-hunt]."

- Chapter 9:
  - L1572: precision → ok
  - Fig. 57 caption: Suggest to put "Hadrography" in quotes → ok

- Fig. 57 caption: of the CMS tracking system → ok
- Fig. 57 caption: first barrel layer → ok
- Fig. 58: I found it confusing that the units in the plot are in cm, but beam spot coordinates you give the caption is in mm. Suggest to use cm throughout. → ok
- L1627: proper minus sign for -1.76 mm → ok
- L1638: "summarizes the final results" is promising too much, the table merely shows the reconstructed rail positions → rephrased