Table of Contents

The CMS Phase-1 Pixel Detector Upgrade

Abstract

The original CMS pixel detector has been replaced with an upgraded pixel system in the LHC winter shutdown 2016/2017. The design of the upgraded CMS pixel detector allows to cope with the higher instantaneaous luminosities that have been achieved by the LHC after the first long shutdown of the accelerator. The new upgraded detector has higher tracking efficiency and lower mass with four barrel layers and three forward/backward disks to provide a hit coverage up to absolute pseudorapidities of 2.5. This paper describes the design and construction of the CMS Phase-1 pixel detector as well as its performance during collision data-taking.

General information

- Contact persons: Lea Caminada, Will Johns, Danek Kotlinski
- Author list: full tracker author list
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Reviewers

- Anadi Canepa (chair), Ulrich Husemann, Andrea Venturi, Katja Klein (ex-officio)

Paper version after JINST reviewer comments

- Revised version: papermain_revised.pdf

Paper version submitted to JINST

- Phase1PaperDraft_v17.1.pdf
- JINST.pdf

TWR version and follow up

- Phase1PaperDraft_v11.1.pdf
- Comments by Katja to this draft (12.6.2020): pdf
- Answers to Katja (12.6.2020): pdf
- New draft: Phase1PaperDraft_v13.pdf

Paper draft TWR

- Phase1PaperDraft_TWR.pdf

Comments on TWR version

- Comments by the Cornell group
- Comments by the Perugia group
- Comments by the Hamburg group
- Comments by the Brussels group
- Comments by Ben Kilminster
- Comments by Erik Butz

- Comments by Patrick Connor, Doris Eckstein and Rainer Mankel
- Comments by the KIT group

Answers to comments on TWR version

- Answers to comments by the Cornell group
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- Answers to comments Erik Butz
- Answers to comments by Patrick Connor, Doris Eckstein and Rainer Mankel
- Comments by the KIT group

Paper draft history

- 19.7.2020 Phase1PaperDraft_v17.1.pdf
- 17.7.2020 Phase1PaperDraft_v17.pdf
- 17.7.2020 Phase1PaperDraft_v16.pdf
- 30.6.2020 Phase1PaperDraft_v15.pdf
- 22.6.2020 Phase1PaperDraft_v14.pdf
- 15.6.2020 Phase1PaperDraft_v13.pdf
- 12.6.2020 Phase1PaperDraft_v12.pdf
- 3.6.2020 Phase1PaperDraft_v11.1.pdf
- 1.6.2020 Phase1PaperDraft_v11.pdf
- 28.5.2020 Phase1PaperDraft_v10.pdf
- 23.3.2020 Phase1PaperDraft_v9.pdf
- 11.3.2020 Phase1PaperDraft_v8.pdf
- 6.3.2020 Phase1PaperDraft_v7.pdf
- 26.2.2020 Phase1PaperDraft_v6.pdf
- 12.2.2020 Phase1PaperDraft_v5.pdf
- 31.1.2020 Phase1PaperDraft_v4.pdf
- 21.1.2020 Phase1PaperDraft_v3.pdf
- 17.11.2019 Phase1PaperDraft_v2.pdf
- 19.6.2019 Phase1PaperDraft_v1.pdf
- 19.2.2019 Phase1PaperDraft_v0.pdf

Comments on v4

- Comments by Andrea on v4 13.02.2020
- Answers for Andrea

Comments on v3

Answers to comments by Anadi v3: pdf

Comments by Katja on V3, 28.01.2020: pdf

Answers to comments by Katja on V3, 31.01.2020: pdf

Comments by Ulrich on v3/v4, 02.02.2020:

Answers to comments by Ulrich on V3 and V4, 12.02.2020: pdf

Note: Draft v4 reached me in the middle of reading v3. This is why my comments up to and including Section 7.3 are on v3, while everything starting from Section 7.4 refers to v4.

More... Close
Line-by-line comments on v3:

- Abstract: "new upgraded" seems redundant
- L68: do you want to include the extension of LS2 until May 2021
- Table 1: spurious comma in z position of L2
- L136: of course, also L3/4 will stay operational
- Table 2: remove white space at the end of units in square brackets
- L170: make spelling consistent with what SINTEF have on their web page: SINTEF Micro-systems and Sensors (capitalization and hyphenation)
- L170: to achieve optimal yield (remove an)
- L231: add comma after μm
- L282: main changes compared to?
- L292: pleas use correct name of the company and the cyclotron that is used: proton beam at ZAG Zyklotron AG in Karlsruhe, Germany (or: proton beam at the Karlsruher Kompaktzyklotron KAZ)
- L306: maybe: double column unit?
- L328: the section on the PROC600 could be more balanced in two aspects: 1) the discussion of the timing error is much more detailed that anything else in this chapter and could be shortened. 2) the high in-time threshold problem is only discussed much later (L1438) and could be moved here.
- L416: use a better verb than to have? e.g. contain? feature?
- L434: remove hyphens in center to center (only needs hyphens if used as adjective)
- L588: remove hyphens in pixel to pixel
- L592: these days most scientific text speak of standard deviation instead of RMS
- Fig 15: axis titles and labels could be larger
- L678/9: two consecutive sentences with "is at", consider rewording
- L715: several months (plural)
- L744: a CO2 cooling plant (don't know how many there are at FNAL)
- L745: suggest to add cross reference to cooling chapter
- L747: the discussion of the dynamic range of the camera would fit better to the caption of Fig. 21
- L922: suggest to remove "so-called"
- L926: Finally, electromagnetic shielding
- Fig. 27: adjust pictures to exactly the same height
- L1044: suggest "mixture returns to the cooling plant"
- L1082: remove hyphen in "in between" (twice)
- L1087: manifolds distribute the liquid (present tense, not present continuous)
- L1092: remove hyphen in "in between"

Line-by-line comments on v4:

- L1101: is "intensive" the right word to characterize the tests?
- L1133: suggest to expand "A pilot system for the Phase 1 pixel detector"
- L1135: The pilot system consisted...
- L1183: suggest past tense everywhere: The hub address ... was set
- L1211: unclear what "All components" relates to, better specify this
- L1369: "cosmic data" is jargon, suggest at least "cosmic-ray data"
- L1418: RMS -> standard deviation
- L1420: RMS -> standard deviation
- L1438: suggest to introduce the time walk and in-time threshold issue in Section 3.2
- L1506: from pp collisions (just to be clear)

- Fig 43: readers may have difficulties to identify the axis title "Time Delay (ns)" with the term "clock phase" in the caption, suggest to explain this briefly in the caption
- L1520: mention that this is the replacement for Run 3
- L1524: cosmic-ray and pp collision data
- L1528: microns -> micrometers
- L1529: "ladder/panel level" is a little too concise for the uninitiated reader to bear with you, suggest to expand on this.
- L1561: in the reconstruction algorithm/step?
- L1572: suggest: from the other layers
- L1576: what does "It" relate to?
- L1589: introduce abbreviation LA here
- L1590: The LA depends...
- L1628: I would prefer a more quantitative statement than "still far lower"
- L1634: The position resolution is sensitive...
- L1637: In this method, the tracks ... are used to predict...
- L1638: remove hyphen in "in between"
- Fig 48: the light green of the Student-t fit may not display well on projectors, suggest to change into darker green color

Comments on v2

Comments by Katja on V2, 1.12.2019: pdf

Comments by Andrea on V2 9.12.2019

pdf

Answers to comments on v2

- Answers for Katja: pdf
- Answers for Anadi : pdf
- Answers for Andrea : pdf
- Answers for Ulrich : pdf

Comments on v1

Comments by Anadi on V1, 25.7.2019: pdf

Answers: pdf

Comments by Katja on V1, 22.7.2019: pdf

Answers: pdf

Comments by Ulrich on v1, finished on June 30:

Answers: pdf

More... Close
General comments:

- Thank you very much for the new draft, which is very much improved in the chapters that I had many comments on last time

- I've given my input on chapter 3.4 in a response to a request by Wolfram Erdmann, including theses that I think are worth refering to

Line-by-line comments:

- L64: no comma after "modifications"
- L73: "summary and conclusions **are** given"
- Table 1: The information advertised in the caption isn't in the table, I sonly see radius, z position and number of modules
- L100: typo: "shown"
- L137: small i in "Since"
- Table 2:
    - ♦ swap order of does and fluence in the caption (or in the table)
    - ♦ use macro 500\fbinv
- L169: add comma after "Germany"
- L181: state more concretely why this is "of advantage": can run underdepleted without losing position resolution (if still away from thresholds)
- L189: after "sensor edges": delete "are"
- L284: suggest to mov the last sentence to the following paragraph, as it is related to the PROC600
- L313: "This can happen often"
- L317: "This **in** itself"
- L331: "arrival of *an" L1 trigger signal"
- L359: delete duplicate sentence "An automatic reset..."
- L405: DESY
- L406: Suggest to add the information that the UBM is electroless nickel plating by PacTech, Nauen, Germany, and that this UBM technology is shared with the KIT process (where the credit goes to DESY)
- L411: "This test verified that"
- Fig. 8: suggest to add the coordinate system you have introduced before, to clarify that this is a side view along the y axis, so the horizontal coordinate is x
- L425: motivate choice of silicon nitride (same/similar coefficient of thermal expansion as silicon)
- L456: the sentence seem strange, maybe the verb is just in the wrong position? "The gantry for ... is software controlled"?
- L465: Sugest to swap words "connected to a PC via USB"
- L492: "*was* considered functional" (you are using past tense for everything else)
- L524: I find "a parallel route designed for..." hard to understand.
- Fig. 12 caption: "internal **calibration** signal"?
- L574: The reader may want to know to what the ROC failure is related if not to the assembly
- L586: "This issue **was** mitigated"
- Fig. 16 caption: The word "facet" is not used in the main text, is it needed here?
- L614: add comma after "Fig. 18"
- L656: remove hyphen between "in" and "turn"
- Fig. 23: I had a hard time connecting the readout parts described in the main text to this figure. tkFEC does not show up in the text, some arrows point to nowhere (from Delay25, CCU I2C, TPLL, ...)
- L775: "data streams" (plural)
- L867: suggest to change order of words "the core is made from plastics since ferrite..."
- L869: reduce AC components of what? noise?
- Fig. 27: I do not know where to look for the cooling blocks, so I cannot tell where they are on the right-hand side picture
- L944: suggest to move "In general" to beginning of sentence
- L966: "expected to cure **the** problem"
- L974: "very small" is rather unspecific. Is it refering to the diameter, wall thickness, length, ...?
- L975: why "also" simple
- L984: at some point (here or earlier) you need to mention that the two phases are liquid and vapor

- L987: remove "at" after "slightly above"
- Fig. 28:
    - Upper plot: red text on green background is hard to read (for the color blind), axis labels much too small
    - Lower plot: it would help to match the six points of the cycle from the upper plot if the labels (number with circle) were the same as in the upper plot
    - Caption: upper and lower plot swapped
- L1000: "estimated maximum"
- L1001: "stage *was*"
- Fig. 30: figure would profit from larger labels and higher resolution (or vector graphics)
- L1078: integration of what?
- L1084: remove comma after "test stand"
- L1084: typo "separate"
- L1100: remove redundant sentence "The problem with..."
- L1106: This sentence is part of the motivation for the pilot system and should be moved to the beginning of the chapter
- L1140: typo "four"
- L1182: replace number 4 with word "four" (twice)
- L1202: "commercial *airplane*"?
- L1217: typo "connections"
- L1234: replace number 9 with word "nine"
- L1236: replace numbers 9 and 7 with words "nine" and "seven"
- L1266: suggest to add "*optical* fiber plant"
- L1269: spell out acronym MFS (I found "Ministerium fuer Staatssicherheit", vulgo "Stasi")
- L1341: "further delays are added" sounds strange to me, maybe "The LCDS driver chip is used to add further fixed-time (length?) delay lines to each modules"
- Fig. 42: suggest to add the 0.1 mA minimum output current as a horizontal line in the figure
- L1378: remove redundant sentence "Therefore the threshold"
- L1389: "measuring the SCurve" sounds too colloquial, suggest "performing the SCurve test described in chapter 3.6" (where SCurve typeset this way is the name of test, not of the curve)
- L1423: suggest to add "leading to (extented) charge clusters" after "of collected electrons", as you are refering to "clusters" later on. You may instead move the sentence in L1522 here, including the reference [3]
- L1427: point reader to chapter 3.6, where the test is described
- L1429: how the gain and pedestal are determined has been explained before, suggest to delete and point to that chapter
- L1432: typo "pedestal"
- L1521: "convert the charge ... to electrons" sounds a little too colloquial, maybe "express the charge in units of (minus) the elementary charge"
- Fig. 47:
    - Is this really just a Landau distribution, or convoluted with a Gaussian?
    - "increased **number** of clusters"
    - "the broken cluster caused by..." cannot be appreciated without further explanation
- L1547: "difference *is*"
- L1552: introduce LA as an acronym for "Lorentz angle" here
- L1564: "Saturation is never" (delete "A")
- L1573: suggest to move sentence in L1610/1611 here
- Fig. 50: suggest to make plot less busy by removed all but four (or so) sets of points at different lumis
- L1590: "these signals" -> "the corresponding smaller signals"
- L1600: "The **measured leakage currents** are shown
- L1602: which leakage current formula do you refer to?
- L1610: move sentence to L1573?
- L1618: use degree symbol?
- L1625: explain "shallow tracks" better, maybe "tracks with shallow incident angles to the sensor

surface"
- L1626: are these clusters "long" or "wide"?
- L1643: "temporary loss of data" is misleading. The data that is lost cannot be recovered. Suggest "temporary inefficiency due to the loss of data"
- L1653: does 97.5% refer to 1.9e34 as Fig. 54 suggests? If so, state in the text to make it comparable to the "well below 90%" in L1655
- L1662: "*position* resolution?
- L1664: suggest to remove "so-called", as "triplet" is already in quotes
- L1694: improve typesetting of sqrt(2/3), bar does not extend to 2/3
- L1694: motivate factor of sqrt(2/3)
- Fig. 55: axis titles of FPIX plots: "Residuals r direction" and "Residuals phi direction"
- L1690: "The **upgraded** system"
- L1690: do you also want to mention the benefits of the fourth layer in addition to the better readout?
- L1740: S. K\"onig
- L1748: suggest to cite the 2003 IEEE paper by A. Huffman et al. on the RTI process
- L1749: This is not a CMS paper but a short author list paper, "M. Caselle et al."
- L1819: This is not a CMS paper but a proceedings report, author: "B. Akgun"
- L1827: "M. Schr\"oder"
- L1836: this was a Master's thesis, not a PhD thesis

Comments by Andrea 23.07.2019

pdf file Answers: pdf

Comments on v0

Comments by Katja, 22.3.2019: pdf

More... Close
Answers: pdf

Comments by Ulrich, finished on March 18:

More... Close
Answers: pdf

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...
- 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)

- Chapter 1:
  - L2: at the CERN Large Hadron Collider (LHC)
  - 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.
  - 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"
  - 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...
  - L27: In this paper, the design... is reviewed and its performance ... is presented. (a paper cannot do anything actively)
  - L34: Reference to chapter 9 (nuclear interactions) missing
- Chapter 2:
  - L38: upgraded pixel system
  - L41: to have four-hit coverage
  - L43: suggest to also mention redundancy from fourth layer
  - 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 ...
  - L49: upgraded pixel detector system
  - L51: supporting eight detector modules
  - L56: upgraded pixel detector system
  - Table 1: add header row for BPIX: Layer | Radius | Number of ladders | Number of modules
  - Fig. 1: upgraded pixel detector
  - L64: suggest to introduce jargon word "services" here (why do you mentioned power cables and fibers separately, are they not part of the services?)
  - L65: upgraded pixel detector has 1.9 times ... than the original pixel detector
  - L67: The upgraded pixel detector system
  - L69: readout and power systems (plural)
  - L79: why do you only mention ionizing radiation, but not NIEL fluence (which is very relevant for the sensors)?
  - L81: The upgraded pixel detector maintains... and overcomes limitations of the original pixel detector at higher luminosities.
- Chapter 3:
  - L84: remove
  - L85: upgraded pixel detector
  - L87: array of 2x8
  - L94: "upgrade modules" sound strange, maybe: upgraded (pixel) detector modules?
  - L102: this section is very difficult to understand for non-experts on silicon sensors, see detailed comments below
    - L105: suggest to delete: as described...
    - 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...
    - 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.

    - ◊ 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.
    - ◊ 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)
    - ◊ L118: the concept of guard rings may also not be familiar to the reader, please add a small explanation
    - ◊ 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.
- ♦ L129: The small gaps ... also facilitate the implementation of punch through bias structures, the bias dots.
- ♦ 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.
- ♦ L133: explain FZ, e.g.: wafers from silicon monocrystals produced in the float-zone (FZ) process.
- ♦ Fig. 5: More information in caption, e.g.: Photographs of four pixel cells on a BPIX sensor (a) and on an FPIX sensor (b)>
- ♦ L141: reverse bias voltage.
- ♦ 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?
- ♦ L154: wouldn't it be more natural to argue with the band model rather than the E field when talking about radiation damage?
- ♦ L156: is available within the 25-ns bunch crossing rate of the LHC
- ♦ L157: suggest to mention that the threshold of the readout is due to noise
- ♦ L160: This fluence corresponds to
- ♦ L161: Has the signal height been measured before and/or after radiation? Please add this information.
- ♦ 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]"
- ♦ Fig. 6 caption: chemical element not in italics
- ♦ L164: full depletion of what?
- ♦ L165: A higher bias voltage was not...
- ♦ L166: Motivate why 10000 electrons are sufficient, e.g. by moving the information from L170 earlier
- ♦ L172: During the second long shutdown of the LHC (LS2)
- ♦ L175: spatial resolution
- ♦ L180: "significantly higher flux" compared to what?
- ♦ L182: higher than a few tens
- ♦ L189: and in FPIX
- ♦ L191: suggest to add a reference to the column drain mechanism
- ♦ L213: "a counter running behind" sounds strange to me, maybe: a counter delay with respect to the bunch crossing counter...
- ♦ 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
- ♦ L223: spell out acronym ADC the first time you use it
- ♦ L224: spell out acronym FIFO the first time you use it
- ♦ L225: spell out acronym PLL the first time you use it

- L227: cross talk between what?
- L227: time walk of what?
- L228: below 1800 e^-
- L233: shows excellent performance
- L238: data losses ... outer BPIX layer are less
- L241: faster compared to what?
- L258: could be mitigated (conditional) or were mitigated (past tense)?
- L272: a reset signal (to whom?)
- L273: "found and fixed" is jargon, maybe: identified and corrected
- L278: does the time-walk optimization also refer to the revised version of the PROC600?
- L280: cross talk between what?
- Fig. 8: unit on x axis should be cm^2 (superscript missing)
- L282: First state what the TBM actually does, before going into the details and comparing it to the old version
- L292: "same header and trailer timing" remains obscure for non-experts, please explain better
- L297: what is meant by "trigger stack" in this context?
- L299: N in math mode
- L306: what is the TBM stack? Is it the same as the "trigger stack"?
- L313: has there been an outline of the LS2 consolidation work before in this paper?
- L321: four readout links
- 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, ...)
- L354: the µ should be in upright, suggest to use siunitx package.
- L354: the cap was made of Kapton = polyimide, not polyamide
- 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.
  - L366: LabView is a trademark
  - 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.
- 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.
- L384: A suite of tests was performed
- L388: damage (singular, mass noun)
- 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)?
- Fig. 11: plot as it comes out of the box, to be made more pretty
- L408: If the number of signals sent to the pixel and the number of signals read out from the pixel is the same.
- L429: suggest to add erf parameterization to introduce threshold and noise parameters
- 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.
- L460: that there is no hidden sensor damage (mass noun) that manifests itself
- 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.
- L476: metallic films or foils or plates?
- L477: you mean the material (or more precisely: chemical element) of the foil, right?

- Fig. 14: x axis title should be: Hit rate [MHz/cm^2]
- Fig. 15: x axis title: pulse height
- 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. (Either label the points in the plots or add to the caption which data point is which material)
- L486: good timing settings found?
- L492: if I remember correctly, the ratio of leakage currents at 100 V and 150 V was part of the criteria
- L494: add white space between 1088 and (96)
- L499: The number of produced BPIX modules over time is presented
- L503: damage (mass noun)
- Fig. 16: redo plots in same style, label the dashed line in upper plot, add a similar line in lower plot
- Fig. 16 caption: this just shows the number of modules vs. time, not the yield (= percentage of detector-grade modules)

- Chapter 4:
  - L529: spell out acronym CCU?
  - L530: spell out acronym PIA?
  - L547: explain meaning of "balanced" in this context
  - L556: different implementations of what?
  - L564: four humidity sensors
  - L566: stack of three connector boards
  - L571: two DOHs
  - L573: electrical signals
  - L573: Kapton (trademark!) polyimide
  - Fig. 18: will the updated drawing contain labels?
  - L581: seven
  - L582: seven
  - L583: four
  - Fig. 19: add labels to drawing
  - 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, ...
  - L628: passives passive components
  - Fig. 21: add labels to photographs?
  - L714: Delete "At the time of writing..." (Run 2 already over)
  - L716: eliminate the leakage current problem?
  - L720: CO2 cooling as the technology
  - L726: two-phase accumulator
  - Fig. 22: drawing to small, suggest to move phase diagram below cooling system sketch.
  - Fig. 22 caption: add short description of `what` is shown in the drawing and diagram
  - L744: this may be a matter of taste, but I would prefer the requirements (w/o the paragraph on redundancy) before the cooling concept
  - L759: To ensure continuous operation
  - Fig. 23: labels too small
  - Fig. 24: labels too small
  - L772: backup
  - L773: eight cooling loops
  - L784: backup
  - 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)
- Fig. 27: The measurements are

- Chapter 5:
  - L826: half shell underwent
  - L849: use math mode for variable z
  - L857: this chapter has some redundancy with Section 4.3. Refer to that chapter rather than repeating.
  - L864: are joined with
  - L869: use math mode for variable z
  - Fig. 29: label Segments A, B, C on photograph
  - L873: use math mode for variable z
  - L876: is VCR the Swagelok trademark or the acronym for something? In either case, indicate what it is.
  - Fig. 30: labels way too small
  - L919: "identical to Phase 0" is not very useful if you do not know that design. Add a reference?
  - Footnote 4: Dow Corning
  - L939: Cooling lines
  - 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.
  - L953: Kapton polyimide
  - Fig. 33: indicate where the test heaters are located that you mention in the caption
  - L974: why has the radiation hardness only been tested using gammas and not protons and/or neutrons?
  - Fig. 34: all labels way too small
- Chapter 6:
  - L993: access to what?
  - L1029: "could be" (conditional) or "were" (past tense)?
  - L1045: In this paragraph you are mixing present tense and past tense inconsistently. Things that happened once should be in past tense10
  - L1053: delete "neatly"
  - L1064: can "thermal cycle" really be used as a verb?
  - L1072: inside CMS into a fixed position inside CMS?
  - L1076: joined
  - L1086: comma after 2017
  - L1089: "operating the detector cold" is jargon, maybe: operating the detector at -20C (cold test).
  - L1092: leading to short circuits
  - L1095: detector was ready for installation
  - L1109: High quality modules is not well defined here
  - L1112: addresses
  - L1112: flex cables
  - L1122: why "having ... installed"?
  - L1135: flex cable
  - L1146: up to the point where a test?
  - 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?)
  - L1168: delete "in any case"
  - L1180: where joined
  - L1181: out of the transport box directly into the final position?
- Chapter 7:
  - L1258: I would start this section by pointing back to the module tests described in Chapter 3.

- 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..."
- L1278: The thresholds for L1
- L1281: threshold and noise values per ROC
- Fig. 44: use the same abbreviation of "layer" as in the rest of the text, e.g. L1 or Layer 1

- Fig. 44: x axis label should not only show units but the quantity that is plotted (left: threshold (electrons), right: noise (electrons))

- Chapter 8:
  - L1311: "a few additional calibrations" sounds too colloquial to me
  - 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
  - L1320: Suggest to put material on the number of working channels as a separate section
  - Fig. 45: The distributions for L1
  - L1327: fixed is too colloquial repaired, solved, corrected ...
  - L1357: comma after 46,
  - L1357: plateaus
  - L1357: Fig. 46 does also show the plateaus for L3 and L4
  - L1384: link this section to the section on the DC-DC crisis
  - L1395: remind reader that 2019/2020 is LS 2 and will lead to Run 3
  - 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.
  - L1414: fixed corrected
  - Fig. 47: align plots and consider choosing the same x and y axis ranges for both
  - L1425: pixel charge charge collected in a single pixel
  - L1436: suggest to move explanation of charge trapping in the sensor from L1437 up here.
  - 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.
  - 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
  - Fig. 49 caption: mention that the profiles are for different years of data taking, different HV settings, and different annealing times
  - Fig. 50: spell out luminosity in x axis title
  - L1469: More meaningful title? Performance of what?
  - L1484: that is which in turn depends on
  - L1504: Gaussian or a t-student function Gaussian or a Student's t distribution
  - L1507: radial position of the layer
  - L1509: amount of radiation is too unspecific. Do you refer to total dose or fluence?
  - 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.
  - Table 2 caption: in volts
  - 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
  - L1544: in Figs. 53 and 54
  - 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
  - Fig. 5: all labels way too tiny
  - 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)

- Chapter 9:
  - L1572: precision
  - Fig. 57 caption: Suggest to put "Hadrography" in quotes
  - Fig. 57 caption: of the CMS tracking system
  - Fig. 57 caption: first barrel layer
  - 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.
  - L1627: proper minus sign for -1.76 mm
  - L1638: "summarizes the final results" is promising too much, the table merely shows the reconstructed rail positions

Comments by Anadi, finished on March 23:

More... Close
Answers: pdf

General comments:

- the paper is overall very pleasant to read and complete. It will be a valuable document for the future.
- However Sec 1 to 3 (and section 6.3) would benefit from some consolidation. The same piece of information is repeated in various places, leading to redundancy and possible confusion. Table with specs and layout details would be beneficial.
- Also the language is at times too colloquial and not appropriate for a paper. It would good if you could review carefully these sections and ensure that statements are always quantitative and/or supported by references.
- Figures tend to lack units and the format is quite difference from fig to fig. The labels can be fixed (even in the pdf file), it would be good if plots were remade with a common format. I know that the latter is challenging.
- Please review the tense used in the paper (sometime it is past, sometime it is present tense). I expect the CLE to make this remark as well, but it would be quicker if you fixed this while you implement the reviewers comments.

Line by line comments:

- L4 I find this statement a bit vague. I suggest you state the requirements or remove the statement

- L5 Likewise (it is of course a matter of taste) I find the words key , indispensable not appropriate for a paper. I would be factual and state how the pixel info is used.

- L8 (and other cases) I don t think the interaction point is a reference in the CMS system, so you would not be able to define a distance with respect to that. I suggest you add instantaneous in front of luminosity

General comments for Sec 2. Having a high level introduction is very useful, however the risk (as in every paper) is that we use terms that not defined (for example ladder on L51). I would streamline this section. For example I would build the section starting from sensor, then modules, ladder, large structure.

- L44, 45 are the hybrid modules the same as the modules? the sentence may be mis-leading to non expert readers

- L46 the bonding is not electrical per se, I suggest you remove electrically

- L65 While I understand what you mean, I think the correlation between fitting in the same envelope and need for larger bandwidth is not clear. I suggest you reword it.

- L78-92 is a more precise description of the scope of the upgrade, with respect to L22-26. As I mentioned above, I think making sure that the statements in the introduction are more quantitive (for example the requirements in L78-92 could be moved to the introduction) and Sec 2 is consolidated (we don t add qualitative statements when you have a proper rigorous statements in the following section) will help.

Given that the ROC will differ depending on the layers, it would help if you added a table with the requirements for BPIX (for each layer) and FPIX: dose, hit rate, instantaneous luminosity, etc.

- L84 spurious Fig?

- Fig 3 could you make the Fig with the same x axis? If there is a reason for having different x-axis, can you explain?

- L85-ff Likewise above, I think it is better to introduce definition and descriptions only once. Here for example you mentioned the pixel size that was already mentioned in the introduction, and you quote the size of the sensor which is then presented again on L104. I strongly encourage you to go through the paper and make sure there is no redundancy (otherwise the paper becomes hard to read) - it would help make the paper more compact.

Another example of redundancy that could be resolved is on L100 and L122. You state twice that the designs are different but you don t provide the details till L124/143. Please try to consolidate.

- L106-107 the sentence does not flow nicely grammatically

- L117 given that you don t provide cost and schedule for the project, I don t think we have to add this piece of information

Title of 3.1.4 I find height to be a bit jargon. I would simply state "signal". I find this section a bit too pedagogical for a peer reviewed publication. I suggest you remove the explanation of why the signal degrades (I would actually remove the description about the benefit of n-n silicon for the same reason) and give the technical requirements, specifications, description of the CMS specific sensors. Here for example what do you mean by small signal , can you provide the spec of the chip?

- Fig 6 is a bit hard to read. There are more lines that documented in the legend. Can you explain why (adding the explanation to the caption) or fix the plot?

- L167 This is the first time you write about the actual bias voltage. It would be useful to quote the planned range of bias voltages in the silicon sensor section to place this discussion into a context.

- L169 what do you mean by probably ? I suggest you are quantitative. What is the impact of having on average 6k signals on hit finding?

- L171 is 3000e the threshold for Phase1? The number is different on L228. What ROC is used here?

- L172 This piece of information is important but should be introduced ahead, when you discuss the expected range of bias V (in the sensor section)

- L173 how did you estimate 10k from Fig 6?

- L181 Another example of redundancy, you have already stated what your requirement is (600MH/cm2). and the need for a new ROC. Please consider consolidating, you could for example remove L179-185.

- L185 citation for the ROCs? please add here where each chip is used.
- L227-239 by the time the reader reaches this section, they should know what the requirements are, to place the test into a context
- L239 It is not clear why you chose 600MHz/cm2 as the boundary? From Fig 7 one would infer that PROC600 would be needed already for ~150MHz/cm2.
- L241 please add the requirements
- L251 As I wrote above, it would be helpful to have a table of requirements on L71 to help understand with what margin the specs are met
- L253 can you be quantitative? What is the degradation?
- L316-317 A table summarizing the various options and the number of modules per layer would help guide the reader
- L321-322 Are you going to describe how the modules differ? If so please reference the section. If not, I suggest you remove the sentence (or add a detailed explanation) otherwise the reader does not learn much

I don t fully appreciate why the discussion about the production schedule is presented in the paper. I would remove L323-325 and L328. If however you would like to keep it, please add the details of the L1 vs L2/3/4 schedules, what was the schedule driver, etc. Our objective is to have the reader learn about past experiences with detector construction.

- L323 The test itself did not contact the ROC, please reword this sentence (for example the goodness of the bump bonding was verified using)
- L337 how many centers? Please be specific. Also what made a given center capable of that operation? Why not sending all faulty modules to the centers capable of reworking the assembly?
- L349 Do you have an exploded view of the module to help understand the mounting procedure better? Fig 4 is too compact.
- L359 made of > instrumented with
- L373 Was any of the issues reported in FPIX encountered in BPIX? If so, please specify in the previous section
- L382 please add the specs of the thermal testing
- L385 - 388 This test is described together with the others in the following part of the section. Why did you single it out here? I would move whatever relevant information you have here to the 7. IV Test to avoid redundancy and possibly confusion
- L389 do you have a reference for the SW?
- Fig 11 If the z axis is the efficiency why doesn t reach 100% Please explain the figure in the text. Missing units on axis
- L402 and caption of Fig 11 please use subscript where appropriate (thr, Comp, Del)
- Fig 12 would it be possible to make these plot more inform? For example the x axis labels? Also for

BPIX, what is he difference between the dark and light color? Please add the legend. Missing units

- Fig 14 please fix the label Hitrate [MHz/cm2] > Hit rate [MHz/cm^2] . Caption: please explain why the 50 o 120 range is used to determine the efficiency.
- L487 please specify what you mean by defective pixel (i.e. what test the pixel failed)
- L488 is 600 the threshold for both chips?
- Fig 16 please explain what detector grade means in the caption. Bottom plot: too small, hard to read. The black line (received) is not visible, received is not defined. Please add.
- Fig 18 you have a note update picture . Is the picture up to date and the text needs updating or the other way around?

Both Fig 18 and 19 would be more useful if you added a description of the relevant components to the caption.

- L590 any lesson learnt from this test that is worth documenting?
- Sec 4.2.1 given the issue with the DC-DC converters, I think it would be very useful if you went into the details of what QC tests were made during the R&D, preproduction production phases. It is important to document what tests were carried out which - unfortunately - did not spot the issue that would emerge later on during data taking.
- Fig 22 Too small, please move the sub fig on the right to the bottom
- Fig 25 the Fig is a bit hard to read. Please add a detailed explanation to the caption
- L807 what was the conclusion of this test? Again, it would be useful if you documented whether or not the test was successful and reliable for future references.
- L829 I am not sure you refer to Fig 18, as Fig 18 is not labelled
- L890 was the yield 100%?
- L902 please add the dimension of the disks
- L962 is the sag within spec?
- L972 As mentioned above it would be important to expand on QC and explain what (if) issues were encountered or all parts met the specs
- Fig 34 is too small, please expand it. Please explain the Fig in the caption. What is ref 1/2/3? If those are preirradiated samples, why is the variation so large in some cases? For the irradiated samples, the araldite depends strongly on irradiation, please explain.
- Sec 5.2.7 Was any material used by FPIX tested for rad hardness?
- L1009 a reader may wonder why the DC-DC converter issue did not manifest itself in the pilot system. Please add a short explanation about it

General comment to Sec 6.3: the language is frequently too colloquial; technical details ought to be added to actually provide valuable information to the reader. Please have a look at this section again. I also give my

line-by-line comments below.

- L1110 what does the wire bonds were pulled mean?
- Sec 6.3.1 Please specify the temperature and duration of the baking
- L1122, 1123 heavy , bulky too colloquial. Please report the details of the pigtails (size, etc)
- L1136 inadvertent colloquial as well. Please write that cables did not meet specs. Also explain why the issue was not identified ahead of time. Add if any other issue originate from the cables being shorter than needed.
- L1137 went more smoothly again too colloquial
- L1138 in this case as well it would be important to be specific: what flex cables, how many broke, etc.
- L1141 please specify what 2% refers to
- L1147 abrupt too colloquial. Please specify DeltaTem /DeltaTime and explain in detail what issues were observed (including % of bump bonds lost). What was the new procedure? What was the improvement?
- L1152-54 I would have this statement only if it can be made fo FPIX and BPIX. Also, in order to be informative, it should be more quantitative: how many people (students RA senior engineers tech), how many shifts etc?
- Fig 43 please explain the spread among channels. Add units.
- L1280 please quantify, indicate how much the thresholds were changing till we collected 10/fb
- Fig 44 still missing FPIX?
- Fig 45 unfortunately the colors are really hard to distinguish
- L1317 how long?
- L1320 Previously it was stated that only 0.4% of the BPIX channel only 2% of the overall FPIX were lost. Could you please explain how you get to 98.4 and 96.1%?
- L1343 what reduced the number from 100% to 96.7% after the DC-DC fix?
- L1376-1384 The language is too colloquial (mistake, unpleasant, periodically,). Please review this part. Provide additional details about what transistor was actually causing the problem. Add the length of the power cycle and the corresponding down time.
- L1384 I assume that a study of efficiency was made, in comparing the two approaches: reset during fill and in between fills. Can you please support the decision taken in a quantitative manner?
- L1390 It would be useful to have a table with the threshold (spec, during data taking) for the 2 chips. On L228 we mention 1800e for the PSI46dig, on L171 we have 3000e (not clear for which one of the two chips) and here we state that instead of 2000e we lower the threshold to 1300e for PROC600. I assume the final numbers are provided on L1405-6. A Tab like Tab 2 for HV would be useful
- L1382 why is Fig 51 here? Some issues with the numbering of the Fig (it should be 47)

- L1418 please reword sudden jump
- Fig 47 please align the plots
- Fig 48 please explain the shape of L1
- Fig 50/52 is this the latest plot?
- Fig 55 is vey had to read. Please produce it again with a different format or include a description of the markers in the caption. Why is data/sim better in 2018?
- Fig 56 likewise for the start of 2017. Please enlarge this fig (it uses anyway the full page)

Comments by Andrea, started to be filled on April 4th (last update on April 23rd 10h30):

More... Close
Answers: pdf

The paper is very nice and full of useful information. It is long but at this round of comment I will not try to suggest way to make it shorter. This does not mean we should not try later...

Paper organization (last update on April 4th)

- The sub-sub-section 3.1.1, 3.1.2, 3.1.3, 3.1.4 are not needed. Their content fits very well one after the other without the need of a sub-sub-title. Minor changes are needed around rows 103, 124, 143 and 153 to compensate for the absence of the titles. The text in rows 96-101 should be, eventually re-checked to avoid unnecessary duplications with what is described below (for example rows 104-107). There is no need of a new paragraph between row 97 and 98
- The sub-sub-sections 3.2.1 and 3.2.2 are not needed. The fact that we have two ROCs is well explained in rows 185-187 and it is enough to start the paragraphs about PSI46dig (row 189) and the paragraphs about PROC600 (row 241) in the proper way (as it is now it could be already ok) to make clear that we are talking of one or the other ROC
- No need to break and start a new paragraph between row 277 and 278
- There is no real need for sub-sub-section 3.6.1, 3.6.2 and 3.6.3. These three parts fit very well one after the other we no need for a dedicated title.
- Section 3.6.1 text could be better organized. The text in rows 388-392 could be moved earlier, about row 384 and replace the sentence about testing procedure is described below . The details about the different temperatures given in row 387 are a repetition of what is written in row 459. There is no need to write them in the introduction to the tests (unless ALL the tests are done at two temperatures but in this case the fact that only in row 459 this is reminded is misleading). The preliminary tests described in rows 394-404 and the tests described in rows 406-461 should not appear as something different and presented with different styles. In particular the titles of the tests in rows 406-461 should be removed (and, if needed, the text at the beginning of the description of each test adjusted). Moreover, the sentence Before starting the testing procedure all modules were tested does not sound OK. There is no need to split between pre-test and test in a public paper.
- The sentence about rejected modules in row 414 has to be moved where the module grading is described.
- Since, I guess, the threshold trimming is done by using the results of the S-curve, the paragraph in rows 416-422 and the one in rows 424-431 have to be coordinated better. One possibility is to swap

them and explain that the iterative process for the trimming consists of repeating the S-curve measurements. In any case it is not clear in the trimming paragraph what is the observable used to iterate.

- The details on how the threshold and the noise is extracted from the S-curve have to be moved from section 7.4 to the paragraph in rows 424-431. Section 7.4 can refer to this section later.

- The gain and pedestal measurement described in rows 438-446 is repeated also in section 7.5. Can you move here the description or make an explicit forward reference to section 7.5 (as of now I am not able to judge which solution would be better)

- Section 4 has to be removed since the statement of rows 510-512 is, correctly, already in the introduction. Sub-sections 4.1, 4.2 and 4.3 have to be upgraded to be sections.

- Section 5 has to be moved before subsection 4.1 and 4.2 (not before 4.3, though): having the mechanics and service cylinders already described help a lot the description of the readout and power system.

- Rows 899-900 do not contain a good introduction to the whole FPIX mechanics sub-section since they describe only the FPIX disks (!). No introduction was present in section 5.1 . Think about removing all the sub-sub-section 5.1.x and 5.2.x. In particular 5.2.3 is really a short sub-sub-section.

- The text of sub-sub-section 5.2.5 has to be merged where the service cylinder mechanics is described since it completes its description

- The text of the sub-sub-section 5.2.6 has to be moved where the disk mechanics is described: it completes its description.

- The Pilot system deserves its own section. Not a subsection of section 6 (it does not even match with the title, to some extent).

- Sub-Sub-sections 6.2.1, 6.2.2, 6.2.3 can be removed: the three parts fit nicely in a single section with, maybe, a bit of rewording at the beginning of each part.

- The description of the TBM hub address should be moved where the TBM chip is described. (rows 1023-1027).

- Section 6.3: the sub-sub-section titles can be removed and the time evolution of the FPIX integration, now described in row 1097-1104, can be distributed later: after line 1119 for the module integration to disks, after line 1153 for the integration of the service cylinder and the shipment (somehow rows 1149-1150 already repeat what is at the beginning of section 6.3 and that I propose to remove)

- What is described in rows 1261-1267 was (partly) already described around row 402. A strategy on where this has to be described and proper (forward/back-)ward references have to be established

- Rows 1268: the threshold trim is already described in row 205: refer to that (or write the sentence assuming that reader know already what the trim is.

- Section 7.5 has to be coordinated with section 3.6.1. For example the sentence about the use of the average slope per column (ropws 444-445) can be moved in section 7.5 (since it is more related to the detector operation and reconstruction). Instead what is presented in rows 1304-1308 should be anticipated as much as possible (section 3?) because it helps to convert Vcal into electron and many results before section 7.5 are presented as a function of Vcal. Moving this part is not a problem because the X-ray test is described in section 3.

- The content of rows 1310-1319 can be moved later, when the results with the collision data are discussed (time alignment and resolution). Section 8 can start with the summary of the good channel fraction (starting from row 1320), followed by the description of the DCDC converter issue, the repair campaign and is consequences. A subsection whose title refers to the fraction of active channels could be introduced

- The text of subsection 8.1.3 is not needed. The issue with the present PROC600 is described in the section where PROC600 is described, the issue of the cross talk noise and the consequences on the thresholds are described in section 8.2.1 and the measurement of the efficiency is presented in section 8.3.1 . Remove the text of rows 1386-1396 and, if needed, add more details in the other sections where this is already described

- Section 8.2.1 describes facts and results which are not obtained with collision (or cosmic) data and, therefore, there is no need to delay it so much. This part has to be moved in section 7.4 so that we have described in a single place and in a compact form everything about the thresholds: how they are tuned, measured, trimmed, how they evolved with radiation and the issue with PROC600.

- Section 8.1 contains sub-sub-sections which have little to do among each other: time-alignment (which is done once) and the procedure to mask and recover bad channels. These two sub-sub-sections have to be de-coupled.

- Section 8.1.1 should be completed with the statements about the alignment (now in rows 1310-1317) and its title should changed into something like Detector calibration (or tuning) with first collisions . It fits well after the part about the fraction of active channels (see comment above)

- Section 8.1.2 is the ONLY section which is purely about routine operation. Since it describes how unresponsive channels are masked dynamically (actually it does not but it has to be expanded (just a bit) to describe the Soft Error Recovery procedure) and, eventually, focus on the stuck-TBM issue as an annoying example (which requires a special treatment), this section can be moved AS IT IS at the end of the DAQ session (now 4.1) because it describes issues already introduced (TBM sensitivity to SEU) and that are addressed only with DAQ/power tools. In this way we avoid long range forward/backward references

- Section 8.2.2 and 8.2.3 can be moved into section 8.3 (whose title could be changed slightly into something like Detector response and performance monitoring).

- Section 8.3.3 should be moved as early as possible in the section about detector response and performance monitoring. Being before 8.2.3 helps to understand the LA dependence on the luminosity. The title of section 8.3.3 is not very meaningful. The sensor bias does not evolve by itself. We are showing the results as a function of the bias voltage at different level or irradiation.

- Remove the break between lines 1528 and 1529

- Add a paragraph break in row 1538 at the sentence The sensor properties .

- Section 8.3.4 can be merged into section 8.3.3 (and moved together with it). In this way some statements about FLUKA and the Hamburg model can be unified.

- Section 9 has to be removed. I guess that 90% of what is described in this section (motivations, strategy, analysis technique, performance,) are already in the Nuclear Interaction paper. The only parts which have to be taken are: the fact that we have repeated the analysis with the 2018 data, that we have obtained the results shown in figure (choose only two figures, my suggestion is figure 57 and the left plot of figure 58) and that the beam pipe position is as expected after the adjustement of his position, that the tight tolerance between L1 and the beam pipe is visible and that the two halves of

BPIX are nicely overlapping. All this can be moved at the end of section 6.4 as a conclusion of the installation. This is because, presently, the results of the Nuclear Interaction analysis are not providing anything more than a confirmation of the positions of the different parts and this matter mostly for the installation.

What is missing and has to be added to the paper (last update on April 5th)

- CMS coordinates system has to be described as soon as possible in the paper, as it is done in the CMS papers. This will allow us to continue to refer to it in the rest of the paper (as we already do)
- Module local coordinate system has to be defined as soon as possible when the modules are described. This will allow is to continue to refer to it in the rest of the paper.
- Every time we explain why the number of layers and disks have been increased by one, we have to remind that this is done to increase the redundancy of the detector (in particular for the HLT). For example in row 17, 42, 43
- Around row 57 it has to be reminded that this scheme is needed also to allow detector maintenance and refurbishment also during the short shut down during the Winter break (this will be proven when the replacement of the DCDC converters done in 2017-2018 will be discussed)
- In table 1 the titles of the columns in the BPIX section are missing
- In table 1 the z and RADIAL position of each FPIX INNER and OUTER disks should be quoted. The FPIX table should have six rows, one for each inner and outer disk, and one column more with the radial position.
- Somewhere in the paper (for example in the introduction of section 3) it has to be reminded that the FPIX modules have an important difference with respect to the previous pixel detector: the modules are tilted mostly in the rz plane to achieve charge sharing and that the pixel orientation is with the long side along r, different from the previous detector. This can be done around row 89 where (implicitly) only the BPIX module orientation is explained.
- In row 151 we have to give at least a hint about the specifications for the FPIX sensors. Is there a reference? Can we refer to the Turkish paper?
- Something has to be said or a reference has to be added to remind about the effective type inversion when the sensors are irradiated. This should happen either when the comment about the n-in-n approach ensure high E field close to the pixels after irradiation (row 111-112) or when the signal loss is described (subsubsection 3.1.4)
- Close to line 157 an approximated value of the detection threshold(s) should be provided to guide the reader
- In section 3.2.1 the expected hit rate in BPIX L2 (assuming that this is the largest experienced by PSI46dig, otherwise FPIX inner disk) should be reminded (and compared to the figure quoted in row 235, with the usual caveat that X-ray hit rate is equivalent to a more pessimistic particle hit rate)
- Explore the possibility to add a statement about the ROC and TBM chip wafer probing and the resulting yield. It would make the paper more complete and it can fit in one sentence.
- Around lines 210-212 we are missing the description of the fact that there is a CMS level 1 trigger decision which is transmitted to the modules. The word trigger is introduced all of a sudden and used in a jargon style. To be seen if it is relevant to explain what happens IF a trigger does not arrive, eventually.

- In rows 298 and 300 we have to write what is the setting actually used during Run 2: enabled or disabled?

- In section 3.5 nothing is said about the bump-bonding. See also the comment below about references about bump-bonding techniques. We should also remind that FPIX bare modules are not tested.

- As already suggested above, section 3.6.1 should already contain the information about the Vcal to electron conversion factor because: it is measured with the X-ray test which is in section 3.6.1, and it is important to understand the results about the threshold and the noise which are also in section 3.6.1. Also its dependence on radiation should be described briefly because it may be relevant when the signal and threshold evolution vs luminosity are shown.

- Figure 16: does the BPIX trend plot include also layer 1 modules? From the position of the dashed line (lower than 1184) I would say that it does not while, instead, it has to.

- In rows 535-537 it has to be said that FED, pxFEC, tkFEC are FC7 boards with different, custom, mezzanines. A reference to FC7 boards (L1 trigger upgrade or reference therein?) has to be added.

- Rows 580-582: are we missing gatekeepers and LCDS among the components which populate the FPIX port card? Or do they not exist for FPIX? Sorry for my ignorance.

- Section 4.2 is missing the description of the HV part: we have to remind at least the granularity, maximum possible HV (and remind that we are planning to upgrade it to 800V) and maximum current per channel

- Section 4.2 is missing the description of the LV power system for the auxiliary electronics and the control rings. Briefly we have to remind about it, the LV value, the power supply models (because we do that for the main power system).

- In row 693 we have to write explicitly if we have run with the slow sensing enabled or not, eventually.

- Add in row 698 the luminosity integrated at that time (about 30 fb-1 if I recall correctly) and the dose accumulated by the converter at that time (about 1 Mrad if I am not mistaken).

- In the introduction of section 4.3 (row 720) it has to be described what are the advantage of the 2-phase CO2 cooling: low mass, efficient heat exchange because it is two phase, simple: temperature is controlled only by the pressure in the accumulator,

- In section 4.3.2 we have to remind which pressure values operating at -23 C and at 15 C correspond to. This will make more clear to reader statements which appear later in the paper about the fact that the system has to run at high pressure .

- In section 4.3.2 (or in any case somewhere in the cooling section), it has to be reminded the target vapor quality value (range) at which we would like to operate the detector and we have to remind the flow values at which we have operated the detector cooling loops.

- Around rows 805-806 we can say that based on the results of that test during 2018 run we have reduced the flow in some BPIX cooling loop and gained 0.x C in temperature.

- In section 5.1.1 we should remind that the ladders are alternated at smaller and larger radii values compared to the average values. This could be useful to understand how critical is the rate and radiation effects on the innermost L1 ladders. A picture/drawing like the one in the TDR could be useful.

- In section 5.2.1 the explicit information about how many cooling loops are present per FPIX disks (either the inner+outer disk pair or inner and outer disks separately) should be added. I think that it is trivially one cooling loop per half disk, both for inner and outer.

- Around line 973 the power dissipated in the test figure 33 refers to, has to be indicated.

- In section 6.1 it has to be added that the pilot system was used also to test the novel DCDC converter based power system (noise, SEU sensitivity,) and that some DCDC converters were connected to dummy loads (and some moduled were NOT powered with DCDC converters)

- Around row 1028 we should add that thermal grease was used for the layer 1 module installation

- Around line 1202 we have to write that, eventually we had no issue during the 2017 because of the leak reported above and that the leak was not observed again when the cooling connections were tested again after the 2018 installation (I guess)

- At the end of section 6.4 it has to be said that the same detector insertion procedure and verification was adopted before the 2018 run after the DCDC converter refurbishment and no problem was experienced, confirming that the procedure is well established and reproducible with very little unknowns (or something like that).

- In line 1208 if we want to keep the comment that the tests are done at +17C before lowering the temperature set point we have to explain why: to operate a low temperature the Tracker volume has to be sealed that this does not allow us to intervene on the patch panels if the tests reveal problems that can be fixed in that way.

- Can we add a trend plot of the fraction of (in-)active channels at the end of section 8 (around line 1343)? I would give a try to see how it looks in the paper. Not a strong suggestion, though.

- Around lines 1381-1382 we have to remind that in 2017 the TBMs were power cycled by disabling the DCDC converters and that in 2018 we decided not to do it anymore to avoid to break them

- In section 8.2.1 the logic behind the threshold choice and setting is not described. Nothing is said about what happens when the threshold is set too low, for example. If we want to avoid too many details the CRAFT paper can be referred to, since it contains all the details (assuming that the process remains conceptually the same).

- In what is now section 8.2.1 (but that has to be moved and merged in section 7.4) I would add very briefly about the successful attempt, done at the end of the 2018 run, to reduce the L1 thresholds by xxx electrons (I don t remember the exact value: 500-1000) once we have reduced by software one of the main source of the cross talk noise (no need to go in more details than that)

- Around lines 1524-1528 it has to be said that the observables as a function of the bias voltage are shown at different value of the integrated luminosity.

- Related to figure 53, the concept of the annealing has to be anticipated with respect to line 1547 and better explained: otherwise it is impossible to understand why the curves at different values of the integrated luminosity do not behave monotonically. It looks like the old module behavior measured at 51 fb-1 is less affected by the radiation than that of the new modules after 31.5 fb-1 and the reason is, I guess, the annealing of the old modules. When the annealing is introduced it has to be said very briefly that it usually happens in a (more or less) controlled way during the Winter technical stop by stopping the cooling

- In section 8.3.4 (or wherever the text which is presently there will be moved) it has to be reminded

that the leakage current can be reduced with the annealing (see comment above on when the annealing can be done) but we cannot exaggerate because of the reverse annealing. References are welcome. Highlight that the effect of the annealing is visible in the plots of figure 56.

- Around lines 1567-1568 we have to say something about the possibility to run during Run 3 without any issue related to the leakage current. It is enough to say that given the limits of the power supplies we see no problem to collect ~300-400 fb-1 during Run 3 (we can agree on a sensible value but it is not critical and the sentence can be turned into no problem is expected during Run 3 when at most 300 fb-1 will be collected)

- In figure 58 left (that I suggest to keep and move at the end of section 6.4) a few elements should be indicated with an arrow and a legend and among them the module cable footprints in order to get rid of the sentence presently in line 1623-1624

- Missing references to be added
    - A reference to the TDR has to be added in the introduction. It has to be used to justify why a new detector is needed: higher hit rate: increase the bandwidth and reduce the dynamic inefficiency, more complex events because of the luminosity: increased redundancy (one extra layer), extension of the lifetime,
    - A reference for the n-in-n approach has to be added around row 108. At least we can refer to the CMS detector paper (even if in this case this reference can be anticipated ALSO to row 96)
    - In section 3.4 (and 3.5) we should really try to find sensible references to the different bump-bonding technologies used by the different manufacturers
    - Row 389: is there a reference to pXar? Otherwise it is a bit pointless to refer to it by name.
    - In section 3.6.1 (and later in section 7) reference to old papers where the module calibration procedures are described, should be added. For example the CRAFT paper, CFT-09-001, contains a good description of gain and threshold measurements. It is useful to remind the similarity of some but not all the procedures with the old detector. I don t know if there are other papers/proceedings/public notes which describe these testing procedures, even if they refer to the old detector and modules but are still valid for the upgraded one.
    - Also in section 3.6.2 a reference to the X-ray measurements done for the old detector could be useful (to show similarities and differences w.r.t. the old detector). The CRAFT paper can be used of the reference [18] in that paper.
    - A reference to microTCA has to be added in row 533
    - When the detector alignment is referred to (now at the beginning of section 8) the paper(s) that describe the alignment has to be cited. Even if they refer to the old detector the technique is the same
    - When the detector alignment is referred to (now at the beginning of section 8) we should remind briefly that the alignment procedure had to be repeated once more at the beginning of 2018, after the re-installation, at least for the large structures, the new modules and the modules that were recovered.
    - Around line 1428 a reference to the paper(s) were the pixel local reconstruction is described should be added. Probably TRK-11-001 is ok.
    - References to previous papers where the Lorentz Angle measurement is described have to be added in section 8.2.3. In addition to reference [42] (THERE IS A MISTAKE, REFERENCE [41] AND [42] ARE SWAPPED!!) also CFT-09-001 (the CRAFT paper) and TRK-10-001 (the first tracker performance paper) have to be added.
    - Around lined 1472-1473 remind that the pixel detector is used also for the track seeding and put a reference to TRK-11-001
    - Around line 1499 put a reference to TRK-11-001 and to BTV-16-002.
    - Around lines 1509-1513 references which describe the change of the electric field with the radiation and the increase of the trapping have to be added.

Specific comments to the detector refurbishment and the reasons for that (last update on April 5th)

- In the introduction, in the paragraph which starts at line 27, it has to be stated the in the paper there will be also a description of the issues experienced during the physics run and the modifications that have been implemented during the 2017-2018 winter shutdown and that will be implemented during LS2. These issues and modifications are related to the readout chips, the DCDC converters, not flexible enough time adjustement, the power system and they will be described in the relevant section. With this statement we make clear to the reader that: 1) there will not be a section dedicated to issues and the refurbishment plan, 2) that in a few parts of the paper we will describe something which does not exist yet, 3) and that this part of our paper will not be described with an historical perspective (first the observations, then the investigation and finally the solution) to make the paper more compact.

- In the lines between 169 and 177 we are addressing, more or less explicitly, the detector refurbishment for the first time. This part has to be made clearer. We have to start by saying that we care about the longevity (of BPIX layer 1) up to 300 fb-1 because this will be likely be achieved by Run2+Run3 and, maybe, in Run 3 only. Therefore our first action is to replace layer 1 during LS2 to restart the counter . Secondly, as shown in figure 6, when the fluence is large (2.8e15 is our example) the largest is the HV bias the largest is the signal and, therefore, our second action is to upgrade the power supplies to reach 800V (and a forward reference to the power system section can be added). Thirdly since we had to operate with larger than expected threshold the BPIX layer 1 ASIC (forward reference to where the threshold are described), and the threshold is important (again figure 6 is there to demonstrate that), we have decided to design a new version of PROC600 that will be installed with the new L1 (forward reference to where the new PROC600 is described). Do not use words like currently or presently in this paragraph because they will become misleading in future. I would remove the statement that at 800V we will collect 10000 electron because this is not what is in the plot of figure 6 (and 10000 electron is not such a magic value).

- In line 257 replace the reference to section 8 to a text which explains that we have observed shortcomings for what concern the hit efficiency and the cross-talk noise.

- In the line 262 add a forward reference to the section where the hit efficiency results are shown

- In lines 278-280 add a forward reference to where the thresholds are discussed: now it is section 8.2.1 but this has to be moved and merged in section 7.4. It would be better to be a bit more quantitative on the possible threshold reduction with this changes.

- The description of the problem of the present TBM, now in lines 1376-1378 has to be moved in section 3.3: no need to write in section 3.3 that a new version is needed without explaining what is the problem. In section 3.3 it has also to be said what is the rate of stuck-TBM (for example in L1 0.7% every 100 pb-1, if I recall correctly) and they can be recovered only if there is a power cycle. The details about how the power cycle is implemented and the impact of these power cycles on the DCDC converters can be left in the corresponding sections

- Around line 311 add a forward reference to the detector time alignment section to justify why the delays are added to the TBMs

- Line 467: I just want to flag a tricky issue: we can be asked to explain why we have not observed the issue of the present PROC600 dynamic inefficiency when we did the high rate test. In other words why the red line of figure 8 was not observed. The official explanation is that those tests were done with the reset (by mistake) and, therefore the orange line was measured. But we have to agree if we want to tell this story and what if we do not.

- The title of section 4.2.4 could be changed in something more specific and related to the DCDC converters since it addressed only that issue. In line 712 we should say briefly that we decided to

change all of them because a much larger fraction than the broken ones were found having an anomalous response (or however you want to name it). In line 714 at the time of writing can be removed and in line 716 it can be added that the new version is expected to immune to the problem because it features a path for the leakage current. In this section the sentences about the TBM can be simplified taking into account that the issue (but not the detail of how the power cycle is done) is already described in the TBM section.

- A reminder: what is described in section 8.1.3 should be distributed in the relevant sections and the section 8.1.3 should disappear

- Nota bene: in line 1405 there is a statement with the PROC600 cross talk noise is described in section 3.2.2 while, presently, this is not the case. As I have suggested the noise issue and the higher threshold issue should be described in 3.2.2 and in 7.4 where 8.2.1 will be moved and merged.

Statements that have to be improved (last update on April 6th)

- Line 16: stating that the detector is able to cope pileup 130 with 25 ns bunch spacing means that it can cope with a luminosity of 5.2*10^34 cm-2 s-1 !! This is not what is written in the same sentence. It is true that it can cope with PU~110-130 and L1 rate of 100 kHz for what concern the bandwidth to readout the data from the detector to the central DAQ system, but the dynamic inefficiency will be very large if the bunch spacing were 25ns. Please check and eventually rephrase to make it consistent and accurate.

- Lines 17-18 add a FOUR hits coverage otherwise it could be misleading. And check that it is true that there is a 4 hit coverage up to 2.5

- Line 68: replace the generic existing infrastructure to the existing cables from the power supply racks to the Tracker patch panel inside the CMS magnet bore (or something like that). No need to not to be specific.

- Line 74: module connectors is misleading. The reader could assume that they are the connectors on the modules and wonders how it is possible that they are moved away.

- Lines 81-82 could be improved into something like: thanks to the new features described above (more layers, lighter, closer to the beam, able to cope with higher particle rate), the Phase-1 pixel detector (is expected to?) has the same, or even better performance of the original detector at twice as large luminosity. If not added before, here a reference to the TDR fits nicely.

- Line 85: it has to be specified that it uses a similar module design as the original detector BPIX modules (the FPIX module of the new detector are more similar to the BPIX modules of the old detector than to the FPIX modules of the old detector).

- Line 101: which requirements ??

- Line 116: the double sided processing is needed not because the n-substrate is used but because the n-in-n design is used.

- Line 120: replace the start of the sentence with something like: silicon sensors that collect electrons on the segmented electrodes [the pixels] require an n-side isolation . Also the holes are collected and the sentence as it is now would not be accurate

- Line 200: analog performance sounds too jargon to me. Can you find anything better?

- Line 217: the buffers means that they are introduced before, but they are not. Can you introduce them when the timestamp and the pulse-height information readout is described above?

- Line 221: replace services with optical links which is what matters this time.
- Line 223: I would add CONSEQUENTLY an 8-bit successive approximation ADC
- Line 227: I am not sure but we have to decide if time walk (which is a pretty generic term in English) is clear enough. In the CRAFT paper it is briefly described and eventually there is reference [7] which happens to be reference [8] in our paper. Can we, for the moment, at least add reference [8] just after time walk ?
- Line 238. It has to be indicated the luminosity (or pileup) at which we expect less than 2% losses.
- Line 249: the statement three pending column should be in the PSI46dig section and just reminded here
- Since in lines 266-268 there is no reference to full time stamp buffer it is not clear if and how the statements in lines 264-266 are linked to the ones in lines 266-268
- In line 272 it has to be said that the periodic reset fixed the inefficiency at low luminosity but not the one at large luminosity (forward reference to the section with the efficiency measurement results).
- Line 296. buffered triggers is jargon. What about buffered triggered event data or buffered data of the triggered events
- Line 320. Add The HIT rate in L1 required
- The title of 3.6.1 and line 405 should be changed in module functional tests in my opinion
- In line 385 and 484 the use of the term electrical tests is misleading because also the other tests involve electricity . Look for a better way to classify them
- Line 415: can you clarify if the result of the trimming is used to operate the modules once installed in the detector? If this is the case it could be useful to add it. If not, never mind
- Line 432: it is not clear if the PH optimization has an impact on the module grading or if it has to be considered as one of the preparatory tests and tunings described in lines 394-404. I am not suggesting to move it there but I am wondering if it could be clarified a bit better. Maybe once both the preparatory tests and the tests which are now highlighted with a title and an enumerator will be described with the same style, this would be less of an issue.
- Line 437. I think that the statement is optimized as a function of the injected signal charge should be re-written into something like is optimized by injecting signals with different charge amplitude . Otherwise it looks like there is one optimal setting for each signal amplitude.
- Line 441. It is not defined what this curve refers to. In line 440 a change like and records the MPV of the pulse height distribution as a function of the Vcal DAC setting Only in this way a curve is defined (MPV vs Vcal).
- Line 445 : add something like optimized PH MPV
- Line 451: if the pad used to induce signal to the sensor is not described before (and I think it is not) then you cannot use THE metal pad and you have to use A metal pad
- Lines 471-474. It is not totally clear to me, reading the text, why something special has to be done to identify inefficient double columns instead of, for example, comparing the efficiency of each pixel,

obtained with the pixelalive test and look for clusters of inefficient pixels in the same double column.

- Line 479: is it the mean value or the MPV ?
- Line 500 cumulative production should be modified in something like cumulative production timeline/profile/evolution .
- The problem of the FPIX module noise in lines 504-508 should be described better: calling it a cause for failure seems to indicate the the modules with this problem were NOT installed and they are not among the 816 accepted for installation. But then the sentence about being fully recovered after 10 fb-1 indicates that some of them were installed and therefore they were not only among the 816 but, eventually among the 672 that were installed.
- Line 530: I think that the CCU I2C channels are NOT used to program ROCs and TBMs and, therefore, writing the readout electronics can be misleading. PIA has to be defined (later in the paper it is called parallel interface if I am not mistaken in row 659)
- The pixel specific modified I2C protocol at 40 MHz (line 520 and in many other places) should not be referred with the term I2C because, I think, it is not derived from I2C (ask Wolfram). The use of pixel ad an adjective is jargon. What about a/the custom 40 MHz communication protocol ? To be checked in several places in the paper where, sometimes, it is indicated only as I2C protocol at 40 MHz (which is wrong).
- Line 533: it is not clear between what the 10 Gb/s links are
- Line 540: groups of ROCs should become pairs of ROCs . In any case what is in line 540 and 541 has been already described when the TBM was described and can be removed or made simpler: just remind that there is a 400 Mb/s stream of data from the TBM.
- Line 549: are we sure that new fibers were laid down? My recollection is that no new fiber was deployed between the counting room and the patch panel (and this is how I interpret what is written in line 549). But I can be wrong
- Line 576: clarify that the delays in the LCDS are adjustable (in hardware) but not programmable. Otherwise the reader would wonder why we do not use them to fix the timing issue.
- Line 584: the power boards were not defined before. What are they?
- Lines 583-585. The forward definition of the service cylinders can be avoided if/when the section about the mechanics is moved before the section about the readout system. This part has to be modified either way.
- Line 653: the term another PCB is too generic. What is the name of this board?
- Line 661: strictly speaking saying that the status signals are combined is not enough. Is it an OR? An AND? I know that actually is more complicated than that
- Line 672: is complex the right word or, instead, something like more demanding is more appropriate?
- Line 694: of the fast sensing has to be mentioned it has to be explained what is it for. At which value the output voltage is set to by the fast sensing? Is it in alternative to the slow sensing when the latter is enabled?

- If we need the short introduction of section 4.3 I would try to pass the following message: in a detector based on silicon sensors the cooling system has two purposes: remove the heat produced by the readout electronics (and the sensors) and keep the silicon sensors at a temperature low enough to mitigate the effect of the radiation . but also sounds odd to me.

- Lines 724-728. I would rephrase with the CMS detector as subject: CMS phase-1 pixel detector cooling features the 2-PACL approach which was developed in Nikhef for the AMS and LHCb detector

- Line 734: I would write the other way around it evaporates because it extract the heat produced by the electronics (unless I missing the fact that, in English, extracting can indicate the cause and not only the effect).

- Line 757: using on-detector cooling as a synonym of detector cooling loops and interfaces is a bit too short. To be improved.

- Line 762: clarify that one half of the detector means FPIX or BPIX. Highlight that the two-plant solution allows us to use different temperature set points if we would need it (but we don t).

- Line 796: being able to extract more power (18kW vs 11kW) at -23C when in backup mode sounds odd if it is not justified. Is there a simple explanation? (Maybe I was told and I forgot)

- Line 791 upstream services to be changed into something like services the cooling system relies upon

- Line 800: explain that it is an evaporative CO2 cooling plant

- Line 804-805: the fact that in real life, because of the pressure drop, the temperature can decrease along the cooling loop should be anticipated already in section 4.3.1 as a deviation from the ideal model. Here we can just remind the quantitative result.

- Line 813: is it true that the cooling pipes are the backbone also for the FPIX disks?

- The title of section 5.1.3 could be misleading since there is already a cooling section.

- Line 858: it should not sound as if it is the first time we announce that we use CO2 cooling. Therefore the sentence should be rephrased into something like: because 2-phase CO2 cooling is used, then

- Line 864: those or not cooling loops they are cooling segments or something like that. They become a loop once they are connected together.

- Line 909: quote the inner diameter as done for BPIX

- Line 993: explain access to what

- Line 995 incorporating sounds off

- Line 996: it looks misleading to me: reading this line I have the impression that the mechanics of the third disk has always been present in the old detector and only recently it has been equipped with the modules of the pilot system.

- Line 1000: change into something like before the installation the pilot system was commissioned at a test stand

- I think that the text of lines 1001-1008 should be re-organized a bit. The message to be passed is that the commissioning of the pilot system before the installation and the operation of the pilot system during the 2015 and 2016 run helped us to: improve the design of the TBM, complete the FED f/w, test the DCDC converter SEU sensitivity in the LHC environment, More details can be found in [12]. Everything has to be turned into a positive message more than a list of problems (eventually addressed).

- Line 1052: is it a coincidence that the number of optical fibers is identical to the number of modules?

- Line 1083: clarify if the number of dead channels quoted here are in addition to the ones reported at the end of the installation of the modules on the mechanics

- Line 1115: I think that the fact that two screws are used to hold the modules have been already said when the mechanics is described

- Line 1128: what does integral DCDC converters mean?

- Line 1132: using outer and innermost in the same sentence, one w.r.t. the radius and one w.r.t. the longitudinal axis is confusing. If the installation sequence has to be described it has to be described more clearly.

- Line 1133: is it half cylinder or half disk ? I guess the latter.

- Line 1137. If we want to describe the problem of the cable length, then it has to be made clear how many half cylinders were affected. From the text it is not clear

- Line 1140: was the read-back capability of the ROC ever described before? If it has to be mentioned it has to be said what can be read back.

- Line 1146: if we want to keep the sentence about the calibration, we have to add a forward reference to the calibration procedure. We can also, instead, add later, when the calibration is described, that some half cylinders were tested both at FNAL and later at CERN, to avoid too many forward references.

- Line 1165: transfer lines connecting to the CO2 cooling plant sounds like the whole segment from PP0 to the cooling plant was installed at the beginning of 2017. Instead only between PP0 and PP1 was installed at that time while between PP1 and the cooling plant the installation was done during LS1. Please clarify

- Line 1175: mockup of the installation area should be replaced with mockup of the volume where the pixel detector has to be installed

- Line 1189: no need for a public paper to use different words like cartridges and jumper rails for something that, in case of BPIX was named differently: installation boxes and temporary extension rails.

- Line 1192: I am wondering if in the direction transverse to the beam is proper and clear enough

- Line 1220 : this is NOT I2C communication, at least not the one toward the module, right? See comment above about the 40 MHz custom communication protocol.

- Line 1236: I would replace FED input with FED connector otherwise we give the impression that the FED has only two inputs while it has 24

- Line 1244. Since the TBM delays have been already introduced the sentence should be changed into something like The TBM delays have to be adjusted to synchronize the ROC readout data at 160 Mb/s with the signal transmission speed of 400 MHz

- Line 1321: is infrastructure the right word to be used here?

- Line 1350: the time walk is due to the amplifier but also the comparator (check with H-C)

- Line 1357-1359. The new features of the delays in the new TBM has been already announced. Change the sentence in a way that reflects that: The functionality of the phase adjustement in the TBM will correct this feature

- Figure 47: can we justify why the new layer 1 modules have different thresholds? We have to explain that

- Lines 1464 and 1465. Can we remove mostly ? One method is used for BPIX and one for FPIX, no exception, I guess. Explain that in FPIX a different method has to be used because we do not have shallow angle tracks.

- Line 1467: the luminosity is collected not measured

- Line 1481. The subtle difference between pixel hit (only one pixel) and hit (line 1474) as the full cluster is not well described in this section. We should improve it a bit

- Lines 1489-1490: the fact that there is the reset cannot be ignored when the low luminosity efficiency being above 99% is commented. Something like in L1 the measured efficiency is not affected by the PROC600 issue at low luminosity because of the periodic reset while at high luminosity

- Line 1505: we cannot simply say that the width is referred as the resolution because there is no way to judge the absolute value. We have to say that even if the width depends also on the residual misalignment and partly on the resolution of the other two layers, MC studies and approximated analytical calculation shows that it is proportional to the resolution with a proportionality factor given by (and we can use recent Danek s studies). Otherwise the alternative is to quote MC results and show that we are not that far.

- Line 1515: the starting value of 150 V does not appear in the table 2 !!

- Line 1516: isn t the difference due to the fact that in BPIX it is better never to exceed with the HV setting not to spoil the charge sharing?

- Line 1525 and figure 53. I think that the right figure should be described first so that the full depletion voltage value is presented to the reader before the comment about the efficiency being close to 100% before the full depletion.

- Line 1539 (and before). When the concept of the periodical adjustment and of the optimal value are described, it has to be explained that the chosen value should be such that efficient charge collection is ensured at least until when it is possible to update the value and have the new calibration computed and deployed.

- Line 1541: I would replace predict the depletion voltage with predict the charge collection

- Line 1545: we should clarify that the Hamburg model predict the effective doping concentration which is converted into a depletion voltage with a simple model

- Line 1548: more than this was planned since the beginning I would write this is one of the main feature of the n-in-n sensor concept.

- Around line 1557. I would re-organize the concepts expressed here in this way: the leakage current as a strong dependence on the temperature and, therefore, to avoid, eventually, thermal runaway and/or power supply trips, the cooling has to be efficient and the absolute set point chosen properly.

- Line 1563: comment that also the effect of the annealing during the shutdowns and technical stops is reasonably well simulated

Statements and figures about radiation (fluence and dose) (last update on April 23rd)

- In general: whenever it is possible references have to be cited when values of fluence and dose are quoted. This is more important when they are not consistent with the phase-1 pixel detector upgrade TDR and with the phase-2 tracker upgrade TDR.

- Lines 79 and 229-231: does it correspond to 300 fb-1 or 500 fb-1? According to the figure 9.15 of the TDR it looks like 120 Mrad are reached for 500 fb-1. But it is not easy to judge.

- Lines 159-160: 2.8*10^15 neq cm-2 seems to be too pessimistic for 300 fb-1. In the TDR (bottom of page 116) 3*10^15 for 500 fb-1 are estimated (1.8*10^15 for 300 fb-1). For the phase-2 TDR studies I remember we quotes something like 2*10^16 for 3000 fb-1. Can you verify and eventually justify this figure? If one of the reasons for a more pessimistic figure is the fact that the innermost ladders of layer 1 will experience a significantly larger fluence with respect to the average radius, my suggestion is to quote in table 1 two values for the radii of layer 1: the radius of the innermost ladders and the radius of the outermost ladders, properly explained in the text

- Line 977: it quotes a reference: can it be used for the other lines where the TID is referred to? Is it consistent with what has been quoted for the BPIX? Is it consistent with the phase-1 TDR? I am ok if we want to change with respect for figure 9.15 of the TDR but a sensible reference is needed.

- Table 2: The fluence values quoted for Layer 1 are not consistent with the statement in lines 159-160 about 2.8*10^15 cm-2 at 300 fb-1. They are closer to ~2.1*10^15 cm-2. The ratio of layer 2 and layer 1 fluence is not close to 4, the value we are used to. It is closer to 5: is it justified by a reference? If this is explained by the different fluence between the innermost and outermost layer 1 ladders, I would quote two values for layer 1 (as it is done for FPIX). Furthermore, there are too decimal digits in that table: we do not know the fluence with that accuracy. This table should also be corrected to consider that FPIX ring 1 was biased at 350 V but not FPIX ring 2. I suggest to split FPIX in two columns. Furthermore, the table says that the starting bias value of BPIX was 100V while elsewhere in the paper (line 1515) it is written that it was 150 V. Is it possible to indicate in the table when 2017 ends and 2018 starts?

Units (last update on April 23rd)

- Use consistently in text and plots rad or Gy. rad has to be spelled lower case (lines 79, 976, 977, 980, 982, footnote 8)

- Table 2 caption: cm-2 is missing when the unit is described.

- Gbs to be changed into Gb/s in line 533

Analyses (last update on April 23rd)

- The analysis of figure 49 has to be improved as known by Tanja and Irene. We should not forget to update this plot before submitting the paper

- The analysis of the position resolution (8.3.2) has to be improved is some way because, presently, it does not produce an absolute value of the resolution. Either we explain how to convert (roughly) those values into absolute resolution values (see recent Danek s studies) or we compare to the MC.

- The top right plot of figure 53 and the plot of figure 54: we have to be sure that the different value of the plateau position is not due to a non-corrected drift of the gain calibration instead of a change of the charge collection efficiency.

Plots and figures (last update on April 23rd)

- Figure 2: there is a bit of unbalance between BPIX and FPIX for what concern the level of details. The details about BPIX service cylinders can be in figure 18. Many of the elements described in figure 2 have not been introduced yet (DCDC ,)

- Figure 3: different eta region in the top and bottom plots is not nice. Can we add the curve of the original detector in the bottom plot and reduce the number of plots to 2 ?

- Figure 4: is it possible to add a cross section of a module which shows the sandwich made by rails, ROCs, sensor and HDI? A drawing which resemble the picture here: https://cernbox.cern.ch/index.php/s/IQ7UtInGldjVPhO

- Figure 8: the line v2 with resets could be misleading because in the text we describe the 70 Hz reset. But the reset needed to achieve the good efficiency at high pixel rate for the orange curve has to be issued at every event. My suggestion is to remove it.

- Figure 9: the caption should explain that what is shown is the temporary cable

- Figure 10: BBM should be explained

- Figure 11: it cannot be hit efficiency because the scale goes up to 5. Maybe 5 pixels are injected with signal?

- Figure 12: in one of the four plots the horizontal scale is not in Vcal units (top right). I think that all the plots should feature a horizontal scale in electrons (with the Vcal to electron conversion factor explained before in the text)

- Figure 13: the caption should explain which line is which. Furthermore, the points at low inject charge which are for included in the fits spoil a bit the justification for the tanh fit. Do we need it for this paper? Is it used anywhere in the rest of the paper?

- Figure 15: x and y axis should be swapped. The pulse height as a function of Vcal is measured as a function of the X-ray signal (in electron).

- In figure 16 the separate lines for grade A and grade B for FPIX are not needed because in the text we do not specify if only grade A or A+B are installed (I guess the latter). Therefore the plot should contain Received and A+B . If grade A is relevant for the discussion about the modules with noisy sensors (but for the moment the paper does not link those modules with the grading), then also the grade A only line can be added, but not B only (or C). Clearly the BPIX and FPIX plots should be done with the same style

- Figure 17: should the box PLL become TPLL ? Are the violet lines fast i2c , too? Or are they normal I2C? See my comment above about non-calling fast i2c the communication protocol for the pixel modules

- Figure 18: the letters to identify the sectors and the names of the components should be added

- Figure 19: same comment as for figure 18
- Figure 25: we have to find a way to have the data of those lines to create real plots and not just screen shots.
- Figure 33: It is not clear what -4.2C and max 17.8 refer to. To be clarified or removed if not relevant
- I think that figure 34 can be removed since no significant change has been observed
- Figure 44: August 2017 should be complemented with the amount of integrated luminosity at that time
- Figure 45: colors and styles should be changed to better see the three distributions. Is it possible to plot the Gain distribution (left plot) using electron/ADC as unit by using a default Vcal to electron conversion factor? Even if this is not what we measure explicitly, it is more interesting for an external reader.
- Figure 47: can the two plots combined in one (2017+2018)? Can we have a similar plot for FPIX? Is the first L1 point (at about 2000 electron) relevant? What s its meaning? Can it be removed?
- Figure 48: we have to inform about the luminosity collected when those distributions were measured and we have to explain the low charge tail in layer 1: dynamic inefficiency? Higher thresholds? Spread of pulse height calibration?
- Figure 53: we have to explain/remind what new modules means
- Figure 53 and 54: Avg Norm has to be explained (or a different term used)
- Figure 56: too much (and too small) text. Move the comment about the temperature uncertainty in the caption

Style comments (last update on April 23rd)

- Never use phase-0 , neither in the text nor in the plots (figure 1). Use, as done in many places in the paper, original pixel detector , previous pixel detector ,
- Phase-1 can be used only together with the word upgrade or in the expression Phase-1 pixel detector once this expression has been defined at the beginning of the paper. For example, the title should be The CMS Phase-1 Pixel Detector UPGRADE
- In the paper present and past tense verbs are not used consistently
- Avoid as much as possible the use of the word services and use the correct combination of words: cooling, power cables, optical fibers, There is almost no need to use generic services
- Use the hyphen only when the word compound is used as an adjective. For example double column has to be written WITHOUT the hyphen when column is a noun. Instead double-column inefficiency has to be written with the hyphen. (double column, time walk, base strips,)
- The word pixel is used for too many different purposes. First of all it has to be made clear when we refer to the pixel in the sensor and when we refer to the individual channels in the ROCs: presently pixel is used in both cases and it could be misleading. In other cases pixel is used as adjective at the place of pixel detector as adjective. This is a CMS jargon but cannot be used in

the paper. (lines 454, 519, 526, 1206,

- Is the verb to unify (and unified, unification,) the correct one to be used when the trimming of the thresholds? What about to equalize ? To be checked with someone whose mother tongue is English.
- For BPIX both the terms supply tubes and service cylinders are used: please use only one of the two for clarity.
- Use DCDC or DC-DC consistently in the paper
- I think that rips has to be replaced with ribs
- In FPIX the word ring is used to define two different parts of the detector: the subset of modules at the same radius in a disk (line 53, Table 1, Figure 31) and the carbon fiber structures where the blades are connected to (and that host the cooling pipes) (lines 904, 966, Figure 31 features both cases!!) . My suggestion is to use ring for the latter and use something different (sub-disk?) for the former.

KatjaKlein - 2021-02-22

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