Report of the ITk Pixel Outer System Loaded Local Supports Final Design Review (FDR)

February 28–March 1, 2023
CERN (40-4-C01/zoom)

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Distribution: EB and TCn members, management of the project, participants in the review.

1. Introduction

The ITk Pixel Outer System Loaded Local Supports Final Design Review (FDR) was held on February 28–March 1, 2023. The agenda is available at https://indico.cern.ch/event/1243638 and in the Appendix.

The Inner Tracker (ITk) is the new all-silicon inner tracking detector for ATLAS at the HL-LHC, replacing the present Inner Detector (ID). The ITk is composed of five layers of Si pixel detectors in the inner part (Pixel subsystem) and four layers of Si strip detectors in the outer part (Strip subsystem). The Pixel detector is sub-divided into the Inner System (IS) barrel and endcaps, as well as the Outer Barrel (OB) and the Outer Endcaps (OEC), together referred to as the Outer System (OS). Detector layers are numbered L0 thru L4 in radial direction, with L0 and L1 in the IS and L2—L4 in the OS. The present review covered the loaded local supports of the OB and OEC, focusing on the process of mounting modules onto the bare local supports and the electrical and mechanical performance of the completed object. The bare local supports (mechanical structures and cooling) had already been reviewed previously.

When it is believed that a design is final and ready for production, an FDR reviews all the available data from prototypes to determine how well the design, and the implementation of the design, meet the specifications. For components of a larger system, analysis and measurements demonstrating compatibility with external interfaces, consistent with specifications, are essential. An FDR needs to be held before submission of the final design for pre-production.

If there have been any changes in the design since the last prototypes produced, those changes must be looked at very carefully, hopefully with full simulations. By this time a fully developed Quality Control (QC) plan for production testing should be ready and exercised on some of the prototype components. If the component will operate in a radiation environment, then full irradiation data must also be reviewed. Whatever measures have been taken to ensure reliability should also be reviewed and a Quality Assurance (QA) plan to validate reliability of design and construction or manufacturing techniques should also be defined for review.

The review panel was composed of:

- Christoph Amelung (CERN, chair),
- Jose Bernabeu (Valencia),
- Jens Dopke (RAL),
- Kevin Einsweiler (Berkeley),
- Alexander Grillo (Santa Cruz),
- Marcel Vreeswijk (Nikhef),
- Raphael Vuillermet (CERN),
- Stephanie Yang (Oxford),
- Christian Zeitnitz (Wuppertal),
- Lukasz Zwalinski (CERN),
- Craig Buttar (Glasgow, ex-officio),
- Claudia Gemme (Genova, ex-officio),
- Petra Riedler (CERN, ex-officio),
- Benedetto Gorini (CERN, ex-officio),
- Martin Aleksa (CERN, ex-officio).

The review panel received the following documents ahead of the review:

- Design Overview of the Loaded Local Supports for the ITk Pixel Outer Barrel, AT2-IP-ER-0046, EDMS 2822664, 27/02/2022, Rev. No. 1.1,
- ITk Pixel – Outer Endcaps Loaded Local Supports, AT2-IP-ER-0047, EDMS 2824412, 22/02/2023, Rev. No. 3.6,
- OEC Half Ring Bus Tape Loading Tooling Drawings, EDMS 2827030,
- OEC Bare Half Ring Assembly Drawings, EDMS 2377394.

2. Observations, Recommendations, and Actions

During the review, the specifications and all aspects of the final designs were summarized in presentations. The presentations were clear, very helpful for a deeper understanding, and triggered many useful discussions throughout the review.

The panel acknowledges the very substantial effort to produce the documents and presentations, and warmly thanks the team for the well-prepared review, the very complete and detailed documentation, and the open and in-depth discussions. The panel was very impressed by the work done and the results presented and congratulates the team on this major achievement.

The two provided design books were very useful, they are well-written and comprehensive (but were provided somewhat late before the review, given their volume). The activity is on track, well organized, and even quite advanced in many aspects for an FDR. A few final checks, in particular thermal cycling and post-cycling electrical and system testing as well as metrology of assembled local supports, were not completely finished at the time of the review and need to be continued and concluded.

In addition to many commendable achievements, the panel has identified a number of points of attention, aspects that should be further investigated and worked out, and a number of suggested improvements.

The following points are classified as **O** – Observations, **R** – Recommendations, and **A** – Actions. The actions are requested to be implemented, whereas the team may – after careful consideration – decide to implement or not implement each of the recommendations. The team is asked to take note of the observations. Unless stated otherwise, the recommendations and actions shall be followed up and addressed by the team before the PRR and are to be discussed in a presentation at that meeting.

- **Final design:**
  - **A-1:** As already noted in other reviews, radiation hardness of the re-workable SE4445 adhesive for use in OEC half-rings still needs to be demonstrated. This has been an outstanding issue for a long time and needs to be wrapped up as soon as possible. (It was reported that preparation work for irradiations is ongoing.)
  - **A-2:** Post-irradiation electrical tests of the silver-loaded epoxy (8330D) for the OEC still need to be performed.
  - **A-3:** If not already done, the material budget based on the present final design needs to be checked against specifications, and communicated to and approved by the software and simulation experts.
  - **R-4:** The geometry is described by nominal drawings with no tolerances given therein. Some tolerances are denoted in some descriptive text, but it is unclear what these apply to (e.g. 20 μm for fiducial markers on rings – all of them? Both axes?). No datums are defined on the drawings. This should be improved/clarified for the final production drawings where necessary.

- **Assembly procedure:**
    - **A-5:** For the OEC half-rings, the details of how to ensure sufficiently good alignment between the modules (connectors) and the solder pads on bus tapes so that connectivity of the pig-tails can be ensured at both ends, taking into account the individual dimensional and positioning tolerances of module, pig-tail, and bus tape, still need to be worked out. The solution needs to be demonstrated with more statistics, and needs to be translated to tolerances on drawings and pass/fail criteria for QC checks in such a way that all other requirements for placement (such as overlap in φ between pairs of modules) can be satisfied at the same time.
    - **A-6:** The maximum temperature reached on an actual module while soldering the pig-tail to the solder pad on the bus tape needs to be measured. Soldering has to happen while the pig-tail is plugged in to the module, and heat conduction by the pig-tail might be relevant.
    - **R-7:** In the OB, gluing the pig-tail to the module (for strain relief) prevents the replacement of a faulty pig-tail. Quality control of pig-tails before gluing them to modules is therefore important – a short connectivity check between pig-tail and module before gluing would reduce the risk considerably, in particular if the fraction of faulty pig-tails turns out to be non-negligible.
    - **R-8:** Different module loading techniques and tooling have been developed at the different assembly sites for both the OEC and the OB. This would seem to make it more difficult to dynamically adjust the number of loaded local supports to be produced by each site, e.g. in case of problems with equipment or personnel at a given site. It should be evaluated how this would be handled in practice and how much flexibility there actually exists. Good coordination and preparation of personnel among the sites is needed, even if techniques are different.
    - **R-9:** Different figures of merit were used by different sites to quantify the accuracy of positioning modules on local supports – ΔX and ΔY, $\Delta R = (\Delta X^2 + \Delta Y^2)^{1/2}$ and $\Delta\theta$, of corners or centers (?). While all of them have their merits, for easier comparison between sites it would be advisable to agree on a common choice.
- **Testing of loaded local supports:**
    - **O-10:** The OEC team has carried out significant thermal cycling QA tests using a climate chamber, submitting an L4 ring to a total of 100 cycles from −55 ℃ to +60 ℃, and first results from this test (not yet fully complete) were presented.
    - **A-11:** For the OB, the corresponding thermal cycling, detailed metrology, and re-testing in system test of a longeron demonstrator still remains to be done.
    - **R-12:** Thermal cycling for as many as 100 cycles is a QA test that would not be done frequently, but is very important. In comparison, the QC requirement is much reduced, currently assumed to be −40 ℃ to 40 ℃ for only a single thermal cycle. The team should reconsider this choice, given that there will be many thermal cycles over this range during the lifetime of the detector. At least initially, it would be better to perform more cycles than just a single one, which must cover (at least) the full operating range for Pixels from −45 ℃ to +40 ℃.
    - **R-13:** The test setup in SR1 that is currently being used for operation and thermal cycling of loaded local supports can provide only a very limited range of thermal cycling (down to around −25 ℃ ?) This is limited by the use of the original IBL CO_2 cooling plant. The panel recommends looking for ways to test over the full range of expected temperatures.
    - **A-14:** For the PRR, both thermal cycling and system tests running at low temperatures

(preferably of the previously cycled elements) will be expected for at least a longeron and one half-ring.

- **O-15:** In comparison, the OB system test results appeared more structured and quantitative than the OEC ones. Perhaps a way could be found to display or tabulate measured OEC quantities before and after module loading and thermal cycling in a way that enables quantitative assessments more easily.
- **R-16:** Very few results were shown with Parylene-coated modules. Even if there is no a priori reason to expect particular problems, this is an important additional step, and thermal-cycling tests (followed by electrical tests) of full half-rings for the OEC or full longeron or inclined half-rings for the OB using Parylene-coated modules should be performed as soon as possible (during pre-production).
- **R-17:** It seems that data flexes will not be part of fully integrated OEC rings. However, they will obviously be required for testing, both during integration and after production. It should be considered whether it would be a safer and more convenient approach to connect the data flexes as part of the loading assembly step, leaving the flexes connected permanently and connecting/disconnecting at the other end when required.

- **Grounding and shielding (G&S):**
  - **R-18:** The OB team has carried out a broad program of validating the grounding and shielding performance with noise injection through the cooling pipes. This is a conservative and robust check of the grounding and shielding strategy. It was not possible to generate noise hits in modules, although this technique should be an excellent way to efficiently induce noise into the Pixel ASIC analog front-end. It would be interesting to repeat with a more powerful function generator, trying to find the threshold for actually generating noise hits. (Cf. item O-21.)
  - **A-19:** Equivalent tests of injecting noise through the cooling pipes still need to be performed for the OEC.
  - **O-20:** It was discussed how much noise should be injected onto the cooling pipes to assure there will be sufficient immunity in actual operation. In the presented setup, the amount of noise seen on the pickup coil is at least a measure of what the modules are subjected to in the test (while the amplitude of the noise signal on the injection coil is not). The 2.5–4 V peak-to-peak used in the test seem roughly adequate, but ultimately confirming this (with a measurement on the existing running Pixel detector) is obviously impossible. For a proper G&S design of the ITk, ambient noise of several volts should be unlikely, and the most likely worry would be from some resonant frequency. Probably the best approach is to set some standard for noise on the pickup coil and to test to that level for all module and local support types. A level of 4–5 V p-p on the pickup coil would seem a reasonable choice.
  - **A-21:** The G&S specifications require a system test of the OB (twin-ax shield and opto-panel) and OEC (CAN bus shield) DC referencing scheme. The presented demonstrator results are a very good first step. More tests are required to understand the robustness of the system, including cables of full length.
  - **A-22:** In the OB, the module-to-local-support isolation needs to be checked (DC isolation requirement: 10 MΩ). Ideally, this should be done right after the loading of each module, otherwise after completing the full loading operation.

- **Low-power mode:**
  - **R-23:** First measurements using ITkPixV1.1 modules were made, exploring the performance of the low-power (LP) mode of operations for the SLDOs. These are important measurements for the integration phase of the Pixel detector. The measurements are de-

scribed in the Design document for the OB (Section 6.3.4). However, there seem to be misunderstandings about how the SLDO and the ASIC should be set up and used for the LP case. The LP mode changes the offset for the SLDO, so that a target voltage of 1.5 V can be achieved with a reduced current of roughly 0.5 A per ASIC, thus reducing the power consumed by each ASIC. In order for this to provide access to the various scans, it is important to enable only single core columns. It is recommended that the team consults on the details of LP operation with the relevant ASIC experts.

- **Electrical breaks (outside the scope of the present review):**
  - **A-24:** Electrical breaks in the connections of the OEC local supports to the cooling manifolds were outside the scope of the present review. At the time of the Bare Local Supports FDR, it was not yet clear whether the electrical breaks would be removed from the design – it was later decided to retain them. For the Bare Local Supports PRR, the panel would like to see a detailed discussion of this topic. Have the risk factors been carefully established? Can an electrical break be replaced if it is found to be defective or damaged at any integration stage? Are electrical breaks re-checked for insulation compliance after thermal cycling?
- **MOPS problem:**
  - **A-25:** The performance of the MOPS v1 chip with noise bursts and fluctuating NTC temperature measurements was a concern. It must be established with high priority whether these problems disappear with the use of the MOPS v2 (or the production MOPS v3).
- **Pre-production plans:**
  - **A-26:** Many things were developed and tested with RD53A modules. Because of the major differences between the RD53A and the ITkPixV1.1 ASICs and their performance and operational behavior, it is important that all relevant tests are repeated during pre-production as soon as ITkPix modules and local supports loaded with such modules become available. For this, the assembly of loaded local supports equipped with pre-production ITkPixV1.1 modules must be given very high priority in this period.
  - **R-27:** The pre-production is an opportunity to measure yields, in particular the module and loading ones. This should then inform the rework strategy of the loaded local supports – whether to repair/replace any problematic module immediately, or to put local supports with a problematic module aside and continue production).

3. Summary and final recommendation

The panel considers the review **passed with recommendations.** This recommendation will be submitted for approval to the ATLAS Technical and Upgrade Coordinators.

Executive Summary. The review is passed with recommendations. The panel acknowledges the very substantial effort to produce the documents and presentations, and warmly thanks the team for the well-prepared review, the very complete and detailed documentation, and the open and in-depth discussions. The panel was very impressed by the work done and the results presented and congratulates the team on this major achievement. The activity is on track, well organized, and even quite advanced in many aspects for an FDR. A few final checks, in particular thermal cycling and post-cycling electrical and system testing as well as metrology of assembled local supports, were not completely finished at the time of the review and need to be continued and concluded.

4. Appendix: Agenda

https://indico.cern.ch/event/1243638

Tuesday, 28 February

14:00 → 14:15 **Introduction and Scope of the Review** — 15m
Speaker: Benedikt Vormwald (CERN)
Pixel_LoadedLocalS...

14:15 → 14:25 **Followups from previous reviews** — 10m
Speaker: Dr Jo Pater (University of Manchester (GB))
2023-02-28 Pater B...

14:40 → 15:10 **System recap**

- 14:40 **Outer Barrel Design** — 10m
  Speaker: Susanne Kuehn (CERN)
  Pixel_OB_LoadedLo...
- 14:55 **Outer Endcap Design** — 10m
  Speaker: Dr Jo Pater (University of Manchester (GB))
  2023-02-28 Loaded-...

15:10 → 15:40 **Grounding and Shielding Issues**

- 15:10 **Grounding and Shielding issues - OB** — 10m
  Speaker: Benedikt Vormwald (CERN)
  Pixel_OB_LoadedLo...
- 15:25 **Grounding and Shielding issues - OE** — 10m
  Speaker: Francisca Munoz Sanchez (University of Manchester (GB))
  LLS_FDR_PixelEndc...

15:40 → 18:00 **Outer Endcap Loading and Qualification**

- 15:40 **Half-ring loading: description of techniques and processes** — 30m
  Speaker: Stefano Passaggio (INFN e Universita Genova (IT))
  2023-02-28 - LLS-FD... | 2023-02-28 - LLS-FD...
- 16:25 **OE Half-ring Loading Qualification** — 30m
  Speaker: Ben Harry Smart (Science and Technology Facilities Council STFC (GB))
  2023-02-28 LLS FD...
- 17:10 **OE - Ring-1 system aspects** — 20m
  Speaker: Paul Dervan (University of Liverpool (GB))
  Loaded-LS-FDR-End...
- 17:40 **OE - other Half-ring Loading Qualification topics** — 20m
  Speaker: Simone Ravera (INFN e Universita Genova (IT))
  LLS_fdr_GenovaL4....

Wednesday, 1 March

14:00 → 17:00 **Outer Barrel Loading and Qualification**

- 14:00 **Cell loading: description of techniques and processes** (30m)
  Speaker: Diego Alvarez Feito (CERN)
  Pixel_OB_LoadedLo... Pixel_OB_LoadedLo...
- 14:45 **OB Cell loading: qualification** (30m)
  Speaker: Eric Vigeolas (Centre National de la Recherche Scientifique (FR))
  Pixel_OB_LoadedLo...
- 15:30 **Cell integration: description and processes** (30m)
  Speaker: Andrea Jeremie (Centre National de la Recherche Scientifique (FR))
  Pixel_OB_LoadedLo...
- 16:15 **OB Cell integration: qualification and system test** (30m)
  Speaker: Benedikt Vormwald (CERN)
  Pixel_OB_LoadedLo...

17:00 → 18:00 **QC and schedule aspects**

- 17:00 **OB: QC & production plans** (20m)
  Speaker: Diego Alvarez Feito (CERN)
  Pixel_OB_LoadedLo... Pixel_OB_LoadedLo...
- 17:30 **OE QC plans & procedures** (10m)
  Speaker: Daniel Hynds (University of Oxford (GB))
  OE_QC_plans.pdf
- 17:45 **OE: schedule & (pre-)production plan & site qualification plan** (10m)
  Speaker: Dr Gabriele Chiodini (INFN Lecce & Università del Salento (IT))
  2023-02-28 Loaded-...

The review was concluded by a closed session of the reviewers.