CMS Upgrade Project at HIP

Report for external reviewers
Project period: 01.01.2022 - 31.12.2024
Project leader: Erik Brücken

Background and project overview

The Finnish contributions to the hardware of the CMS experiment are organised and carried out by the HIP CMS Upgrade Project. The contributions include building of new devices, upgrading of existing apparatus and performing ongoing maintenance. The project is coordinated through the Helsinki Institute of Physics (HIP). HIP has the Finnish mandate to coordinate and perform Finnish contribution to the scientific research at large international research centres for particle and nuclear physics, such as CERN of FAIR. HIP as an organisation consists of several institutes in Finland, namely the University of Helsinki, Lappeenranta-Lahti University of Technology LUT, Aalto University and the University of Tampere. The Finnish Radiation and Nuclear Safety Authority (STUK) has been a fixed-term interim member since 2018.

The two main contributions by the HIP CMS upgrade project to the CMS experiment are the inner tracking detector and, the newest CMS addition, the Minimum bias particle Timing Detector (MTD). In MTD, Finland is involved specifically in the Endcap Timing Layer (ETL). Our previous key input has been a substantial contribution to the Level-1 refurbishment of the inner tracking detector. Currently we are focused on the production of the upgrade of the inner tracking detector and the MTD for the High-Luminosity LHC starting 2029.

To develop and support our scientific expertise we run local projects, such as the development of photon counting detectors for medical imaging or Si pixel detectors for high luminosity environments. These side projects are vital in providing our students with the necessary scientific value for graduating.

Progress of the project

The CMS collaboration has been transitioning from the detector R&D phase and market research into the production phase in order to fully build and install the detector parts for the high-luminosity runs of the LHC beginning in 2029.

As our contribution to the inner tracking detector, we are participating in the construction and quality control of the Tracker Extension PiXel modules (TEPX) together with the Ruder Boskovic Institute (RBI) in Croatia. Our team is responsible for the production of 250 TEPX modules.

The Research Council of Finland (RCoF) has granted us infrastructure funding (FIRI) at the end of 2023 to accomplish this task as well as to purchase necessary components (silicon pixel sensors, electronics, etc). Key argument for the funding was to bring part of the production to

Finland and collaborate with the local ALICE group to benefit from common resources and synergy between ALICE and CMS. During 2023 and early 2024 we established a laboratory at CERN to conduct part of the complicated quality control flow of TEPX modules. In addition to the CERN laboratory, we are setting up a full production and quality control laboratory in Helsinki.

Currently we are in the procurement process for needed production devices such as a full automatic wire bonder and a material tester. In addition, two identical module test boxes for the CMS module testing have been built by us; one for the local centre and one for our second production centre at CERN in collaboration with the RBI. These test boxes enable parallel testing of up to 8 modules, allowing electrical stress tests with temperature cycling down to -30°C for quality control purposes.

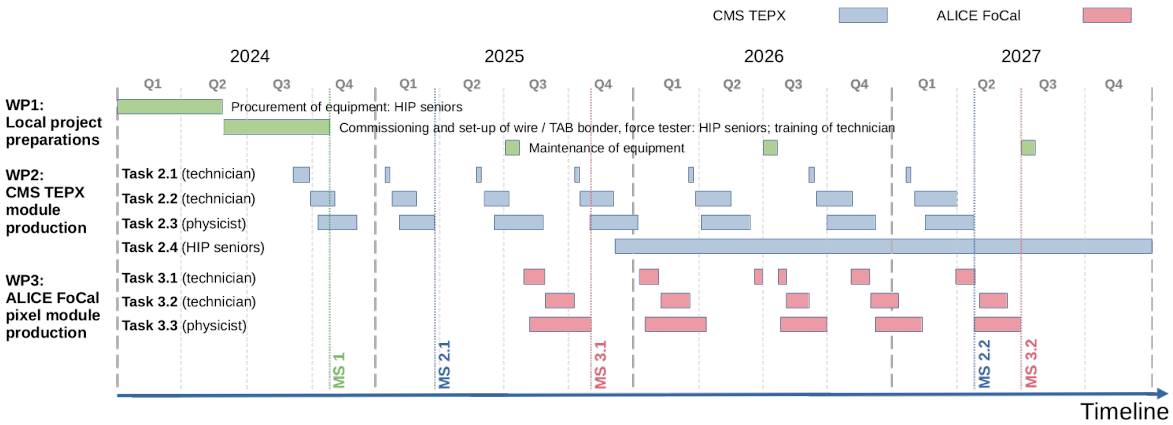

Figure 1: Timeline of the CMS TEPX production

Both centres, CERN and Helsinki, will be ready for operation by autumn 2024, the official start of the inner tracker production. The planned timeline of the TEPX production can be seen in Figure 1 that also includes the planned production of the ALICE FoCal detector pixel layers.

The MTD collaboration has been mainly concentrating on R&D during the present HIP CMS upgrade project period. For the ETL, Low Gain Avalanche Detector (LGAD) technology was chosen. Especially during the years 2022 and 2023 we contributed substantially to the characterization of the test LGADs manufactured by several companies worldwide. Focus was on the radiation hardness and on the study of the active area of the ultra fast silicon sensors. Towards the end we also took part in the market research finding suitable manufacturers for the LGAD production. However, the R&D phase recently concluded with the end of the market research for the sensors. The focus will shift now to the production of the timing detector. We are currently seeking for possible contributions to the production of the ETL.

Local research and development

Over the years we keep up with the tradition to have in house detector development and supporting projects to not only keep our expertise on high level but to develop it further.

At the beginning of this project period we were still finalising the Academy of Finland project “Multispectral Photon-counting for Medical Imaging and Beam characteriza- tion (MPMIB).” due to the pandemic an extension was given until summer 2022. We were able to successfully accomplish the envisioned project objectives. Among those are the in-house manufactured pixel sensors from high-Z materials followed by a successful testing campaign with X-rays up to 300 kV showing the photon counting capabilities with energy discrimination. Also to mention is the successful employment of Si-pixel detectors for beam-profile measurements of Co-60 therapy beam in water reaching sub-mm accuracy. The cumulative research output was 20+ papers, 5 PhD theses and 2 MSc theses.

To follow up on medical imaging related detector R&D, we continued our activity during the last two years focused on Boron Neutron Capture Therapy. Together with the BNCT team at HUS we successfully applied for funding from the Academy of Finland and the Finnish Cancer Foundation. Our objectives within those projects are the testing and development of detectors for measuring the boron concentration in vivo and neutron beam characterization. Currently we prepare a testing campaign with commercially available detectors from our industrial partner Detection Technology Plc. It is foreseen to have first measurement results by the end of spring 2024.

Another currently running project is the development of a thin transmissive silicon drift detector to measure the energy of monochromatic X-ray beam in vivo during X-ray scattering experiments, in collaboration with the HIP IDEAL project under the technology programme. Currently, first designs have been discussed using TCAD tool. High resistivity float-zone wafers were purchased and backside ion implanted before undergoing BSOI process at Okmetic Oy. Once the front side design for the wafers is finalised, processing will start.

Research and development of AC coupled pixel sensors also continued during the present project period. Earlier ALD grown thin layers of alumina and alumina plus hafnia were studied as dielectric material for the devices. Currently we are revisiting this study with a new wafer production with a more controlled separate growth of alumina, hafnia and zirkonia.

Connected to our involvement in the CMS MTD collaboration we also work on a RD50 common project on partial boron activation in LGADs to study ways to mitigate radiation damage in such detectors, especially the detrimental effect of acceptor removal. First samples to be distributed to the participating groups are expected in the end of autumn 2024.

Scientific outcome

During the present project period we submitted and published several articles in known journals. In addition we had active participation in conferences and workshops as well as in networking events and collaboration meetings.

List of publications: (not listed are collaboration wide publications)

- J. Tikkanen et al., *Pixelated silicon detector for radiation beam profile measurements,* Radiat.Meas. 165 (2023) 106949.
- S. Kirschenmann et al., *Multispectral photon-counting for medical imaging and beam characterization – a project review,* Nucl. Instrum. Meth. A 1039 (2022) 167043.
- S. Kirschenmann et al., *Quality assessment of cadmium telluride as a detector material for multispectral medical imaging,* JINST 17 (2022) 01, C01070.
- S. Bharthuar et al., *Characterisation of gamma-irradiated MCz-silicon detectors with a high-K negative oxide as field insulator,* JINST 17 (2022) 12, C12002.
- S. Bharthuar et al., *Characterization of heavily irradiated dielectrics for pixel sensors coupling insulator applications,* Frontiers in materials 8 (2022) 769947.

Educational outcome

During the project period we participated actively in education. Directly linked to the project we had four doctoral students successfully defending their PhD theses:

- **Maria Golovleva**, defence date: 18.11.2022, title: “Numerical simulations of defect modeling in semiconductor radiation detectors”
- **Stefanie Kirschenmann**, defence date: 11.5.2023, title: “Quality Assessment of Detector Material and Prototype Detectors for Multispectral Medical Imaging, with the Focus on Cadmium Telluride and Infrared Microscopy”
- **Shudhashil Bharthuar**, defence date: 16.5.2023, title: “Characterisation of Inter-pixel Termination Strategy and Radiation Hardness Studies of Position-sensitive and Timing Detectors for Future CMS Experiment”
- **Joonas Tikkanen**, defence date: 5.4.2024, title: “Dose measurement improvements in radiation therapy through beam quality correction factors and beam profile measurements”

In addition several undergraduate students were working on their Master’s thesis topic related to the project:

- **Auguste Bieleviciute**, title: “Timing resolution of low gain avalanche detectors after irradiation up to high fluences”
- **Priya Singh**, title: “Development of temperature controlled probe station with Peltier
- elements”
- **Mila Myllymäki**, title: “Position Sensitive Detectors for Quality Control of Proton Therapy Beams”

Proposal for continuation of the project for the years 2025 – 2027

We plan to propose a continuation of this HIP project for another 3 years from 2025 until 2027. Main arguments for a continuation are our currently ongoing involvements in the upgrade of the CMS detectors for the HL-LHC period. The HL-LHC detector upgrade projects will last until the start of run 5, which is currently foreseen for the year 2029.

The CMS TEPX production, explained in detail above, for which we received FIRI funding, will fully cover the proposed 3 year period. A similar project timeline exists for the ETL production for the CMS MTD detector. To realise this project locally as well as to contribute to the core funding of the detector we will apply for FIRI funding during next year's RCoF spring call. Currently we work on details how we eventually contribute to the collaborative effort in building the CMS timing detector.

Local R&D will continue based on similar arguments as mentioned above, namely to enlarge our expertise and maintain high quality doctoral education at HIP. We concentrate on realising the BNCT project together with HUS and strengthen our collaboration with other R&D groups beyond our particle physics community. We plan to also deepen our involvement in the newly formed DRD3 collaboration (successor to RD50) especially on LGAD development and in general on radiation hard semiconductor detectors.

Personnel of the present period

- Erik Brücken, doc, Helsinki, project leader from 1.1.2023
- Panja Luukka, prof, LUT, project leader until 31.12.2022
- Eija Tuominen, doc, Helsinki, senior scientist until 30.4.2023
- Timo Hildén, PhD, Helsinki, senior scientist from 1.7.2022
- Aneliya Karadzhinova-Ferrer, PhD, LUT, post doctoral researcher
- Ahti Karjalainen, PhD, LUT, post doctoral researcher
- Mihaela Bezak, MSc, LUT, PhD student
- Shudhashil Bharthuar, MSc, Helsinki, PhD student until 30.6.2023
- Maria Golovleva, MSc, LUT, PhD student until 31.12.2022
- Stefanie Kirschenmann, Dipl Phys/PhD, Helsinki, PhD student until 30.6.2023, post doctoral researcher from 1.1.2023 until 31.12.2023
- Nikita Kramarenko, MSc, Helsinki, PhD student
- Joonas Tikkanen, MSc, STUK, PhD student until 30.4.2024
- Mika Väänänen, MSc, LUT, PhD student since 1.1.2022
- Santeri Saariokari, MSc, Helsinki, research assistant from 1.10.2022 until 31.12.2023, PhD student since 1.1.2023
- Mila Myllymäki, MSc, Helsinki, Master thesis worker from 1.4.2023 until 31.10.2023, research assistant from 1.2.2024 until 30.4.2024, PhD student from 1.5.2024
- Priya Singh, MSc, Helsinki, Master thesis worker from 1.9.2022 until 28.2.2023
- Auguste Bieleviciute, MSc, Helsinki, Master thesis worker from 1.1.2023 until 31.1.2023