Forum on Tracking Detector Mechanics 2018

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Book of Abstracts

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Mechanical Analysis of the Atlas Strip Endcap Global Support

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For the High-Luminosity LHC a new Mechanical Global Support frame for Strip Endcap of the Atlas Inner Tracker (ITk) (EC for short) is being developed, for this a carbon/epoxy laminate design and prototype have been produced. To match the design to the requirements a finite element model of the system was created for an initial prediction of the mechanical performance, having produced a prototype now allows for validation of individual components and the assembled system to the calculated values.

This talk will bring you from the initial design to building both the physical and simulated variants of the EC, to the current status with the comparison of the results found.

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The OB stave construction of the Alice ITS Upgrade

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The Upgrade of the Inner Tracking System of the Alice Experiment consists of seven detector layers of Si Monolithic Active Pixel Sensors, each with a size of 30mm x15 mm.
The seven layers are organized in an Inner Barrel (IB) consisting of three layers and an Outer Barrel (OB) made of four layers. Each layer forms a cylindrical array of staves around the beam line, with a layout that depends on the radius of the layer. The IB staves (270mm x 15mm) are the assembly of nine pixel chips aligned and connected to a Flex Printed Circuit (FPC) and supported on a carbon plate that also provides cooling.
The OB stave consists of two Half Staves (HS), each made of four or seven Hybrid Integrated Circuits (HIC), aligned and glued on a Cold Plate, with a length of 900 mm or 1500 mm, which corresponds to the Middle Layer (ML) and Outer Layer (OL), respectively.
The Cold Plate is a thin carbon plate, 30mm wide and 300 µm thick, with integrated cooling pipes, which provides the support and the cooling to the chip sensors.
The HIC consists of fourteen pixel chips organized into two rows of seven chips each, glued and electrically connected by means of wire bonds to the FPC. The wire bonds are not encapsulated or protected, enhancing the difficulties of HIC manipulation.
The two HS are supported by a lightweight carbon fiber truss structure referred to as spaceframe.
Tight requirements in the stave construction come from the precision in the sensor alignment and in the very precise knowledge of their final position.
The construction of the IB staves is based at CERN, while five construction sites are in the process of building the OB staves, using identical procedures and mechanical tools to ensure final comparable product quality.
The aim of this work is to describe the procedure for the alignment, the assembly and the qualification of an Outer Barrel stave together with the most relevant mechanical tools designed, produced and used for the different phases.
The main steps of the stave assembly procedure can be summarized as follows:
- The Half-Stave assembly is performed by aligning and gluing four or seven HICs on the cold plate. This operation is performed with tools equipped with vacuum suction systems, which are used for the manipulation and positioning of the HICs in their nominal position by means of micrometric motion stages tuning.

The entire task is achieved on a stainless steel base plate, 1,6 m long, machined with a planarity of 50 µm, which supports and maintains the cold plates in position during the HIC alignment phase. The alignment step is fully controlled by a Coordinate Measuring Machine (CMM) equipped with a video camera. Custom made CMM programs guide the operators during the entire process. The Reference System used for the HICs nominal position is defined by special features machined on the stainless steel base.
- The Stave assembly consists of the alignment and gluing of each HS to the space frame and a carbon fiber bar, 1,6 m long, equipped with vacuum suction cups and reference planes machined with a planarity precision of 100 µm is used. The Reference System used during this step is defined by means of dedicated support structures, on which the experiment official support blocks are glued. The gluing procedure is performed using a master jig which is also used for the gluing of all the stave connectors.
- The metrological survey is the final step of the assembly. A dedicated Jig located under the CMM is used to support the stave during this phase. This step allows to verify the final sensor positions, in 3D volume, exploiting special reference markers placed on the chip surface.
A series of additional tools were developed for a number of operations related to the electrical interconnections. This presentation will focus on the most complex one, used for soldering and manipulating the flex aluminum cable, BUS, used to power the detectors.
Finally, the results of the metrological surveys on the staves produced so far at the different production sites will be presented.

3

CMS tracker alignment

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The all-silicon design of the tracking system of the CMS experiment provided excellent resolution for charged tracks and an efficient tagging of jets during Run1 and Run2 of LHC. CMS upgraded and installed the pixel detector during the shutdown in the beginning of 2017. The position and orientation of tracker, consisting of 15148 silicon strip and 1856 silicon pixel modules needed to be determined with a precision of a few micrometers. The alignment also needs to be quickly recalculated each time the state of the CMS magnet is changed between 0T and 3.8T. We present the results of the CMS tracker alignment, which were derived purely from reconstructed tracks of the collisions and cosmic rays data. The geometries are finally carefully validated with data-driven methods. The monitored quantities include the basic track quantities for tracks from both collisions and cosmic muons and physics observables. We also want to share the valuable experiences and lessons learnt from 2017 commissioning, like how we constrain the weak modes of the alignment algorithm, and how the track-based alignment adjusts for the pixel radiation effects.

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Status report of the UT project for LHCb

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A large upgrade of the LHCb detector is foreseen during the LHC second Long Shutdown when the Upstream Tracker (UT) will replace the currently installed TT. Being composed of new, high-granularity silicon micro-strip planes with a larger coverage, the UT will cope with an instanteneous luminosity of 2x10ˆ33 cmˆ2/s adding up to at least 50 fb-1. It will provide a fast momentum measurement while also improving the overall quality of reconstructed tracks.

The LHC beam pipe traverses the UT body and poses further mechanical and thermal requirements on its construction and operation, especially in the transition regions at the walls of the UT. The UT sensors will be cooled by liquid CO2 to temperatures around -20℃ to improve the lifetime in the presence of a large particle flux. In order to place the UT sensors as close as possible to the beam pipe, thus further improving the LHCb track reconstruction efficiency, yet ensuring safe thermal conditions of the beam pipe, a series of thermal tests has been performed on a prototype. One particular challenge is moreover the alignment of the sensors since a precision of a few hundred microns is desired. Within the scope of additional mechanical tests, the integration of UT components (readout cables, CO2 cooling pipes, supports for services) as well as the alignment of the silicon staves has been studied on a special prototype box. In this presentation, the results of these tests as well as the overall status of the project will be presented.

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Progress Towards the Thermal Management of the CBM Silicon Tracking System

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As the core tracking detector of the CBM experiment, the Silicon Tracking System (STS) located in the dipole magnet (1 Tm) aims to provide track reconstruction (efficiency ≈ 95%) & momentum determination (Δp/p ~ 2%) of charged particles from beam-target interactions (Au-Au at 10 MHz).

Due to the expected irradiation damage (NI dose - 1 x 10ˆ14 neq/cm²), the sensors will dissipate some power (~ 1mW/cm²) and have to be kept at or below -5℃ at all times by complete removal of the heat dissipated by the front-end and read-out electronics boards (~ 40kW). The heat must be removed to avoid thermal runaway and reverse annealing of the irradiated silicon sensors. To achieve this, the STS will be operated in a thermal insulation box and will use bi-phase CO2 cooling system for the electronics.

To efficiently utilise the available CO2 enthalpy:
a) thermal measurements between different thermal interfaces will be shown by using higher thermal conductivity interface materials to replace all the space that otherwise would be occupied by air.
b) operational parameters (e.g. CO2 mass flow, inlet pressure) for an optimised cooling plate design and corresponding Finite Element Analysis results will be presented.

Additionally, for detector operation while maintaining the needed thermal environment with the given space constraints for STS integration, a high-density thermally insulating feedthrough system for all services is needed. In this presentation, the assembly and thermal tests for HV-LV feedthrough panels will be shown.

This is part of an effort towards building a cooling demonstrator for two STS half-stations to show that the CBM-STS cooling concept is viable. The respective future plan for its completion followed by the initial construction R&D will be presented.

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Construction of silicon tracker modules based in synthetic graphite tape with the properties of diamond-like heat spreaders

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Last year we presented the use of diamond-like heat spreaders in the form of cheap Synthetic Graphite Tape (SGT) for cooling of instrumentation in radiation intense environments.The excellent double-sided taping capability of SGT allows to join the support, cooling pipes, sensors and hybrids, leading to "taped modules" without any screwing, which allows in turn for semi-automatic construction by simple one-axe gantries. Also thermal stressed are largely eliminated, since the graphene layers inside SGT allows for slight (reproducible and elastic) sliding of the parts on both sides of the tape. Here we want to discuss our experience with taped modules using the rather complicated CMS double-layer tracker modules as an example. We will discuss the art of construction of ultra-light CF-Airex sandwiches for the support, which were built with high precision in simple home-built thermal hot-presses (vacuum based, no hydraulics), the choice of sandwich materials for such hot-presses, the bending and gluing of hybrids on CF-sandwiches with techniques to avoid delamination in reflow ovens (at temperatures up to 285 ^{0}C), the long-term stability and radiation hardness.

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Mechanical Integration of a Digital Tracking Calorimeter for the Purposes of Proton Computed Tomography

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ABSTRACT

Proton therapy is a novel radiation therapy modality for the treatment of malignant tissues. The high dose gradients that can be achieved using energetic proton beams allow for more conformal treatment plans. However, it has not yet been possible to exploit the full potential of proton therapy due to range uncertainties. An important source of these is the fact that tissue proton stopping

powers are calculated using conventional CT-scans of the patient. Conversion from Hounsfield units to proton stopping power introduces additional uncertainties in the range estimates. To tackle this issue, our group is currently developing a Digital Tracking Calorimeter (DTC) that will be used for proton CT purposes in proton therapy. The DTC will allow measurements of proton stopping power in tissue using high energy proton beams that penetrate the patient. The DTC will enable measurements of the residual range (or energy) and tracks of individual protons crossing the patient with a high accuracy and at higher intensities. This work focuses on the mechanical issues related to the realization of a DTC for the purposes of proton CT. An optimal detector prototype should have maximum integrity, reliability, accessibility, safety and maintenance capabilities. All these features depend on precise mechanical design and analysis of entire calorimeter, stack layers, staves and its constituent elements with regards to mechanical and thermal characteristics. Numerical simulations based on Finite Element Method (FEM) have been performed to model the geometry and mechanical properties of the DTC layers.
Thermo-mechanical analysis of DTC layers consisting of monolithic active pixel sensors interleaved with absorber plates has been accomplished. Sensitivity analyses of mechanical strength and DTC layer deformation have been performed taking into account relevant materials and bonding methods. Additionally, thermal behaviour and heat transfer studies for two coolant fluids have been carried out to find the appropriate cooling solution. The proper solution would avoid risks of mechanical failure for each DTC stack and between the stacks. Accordingly, various cooling schemes have investigated and analysed based on mechanical fabrication reliability and applicability.

Keywords: Proton CT, Digital Tracking Calorimeter, Heat transfer, Temperature distribution.

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Design and construction of the ultra-lightweight Mu3e vertex detector

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The Mu3e collaboration is setting up an experiment to study the decay of a muon into three electrons μ+⟶e+e-e+. Any observation of this decay with the Mu3e experiment would point to physical processes so far not described in the standard model, mediated by the exchange of very heavy particles. Mu3e uses ultra-thin High Voltage –Monolithic Active Pixel Sensors (HV-MAPS) for vertexing and tracking plus scintillating detectors for timing.
Different tools were designed for prototype production as close as possible to series production. Different parts of the vertex detector have been modified during the tooling process to improve manufacturability and functionality.
The prototype half shell which is used for thermal stress tests, consists of four equivalent tape heater ladders and PEI-end rings on both sides. A ladder includes one HDI-flex and a stiffener on both ends. During the mounting process the ladders get connected to each other with a single fold on the long side. It will be shown how we kept up the requirement of a very low material budget combined with a high stability and CTE control.
This poster presentation will focus on the prototype production of the inner pixel layers. Prototypes will be on display.

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LHCb Scintillating Fibre Tracker: Comparison of kinematic and structural FEA with measurements on a prototype

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During the Long Shutdown 2 of the LHC, the LHCb collaboration will replace the current Outer and Inner Tracker by a single tracking detector, based on 2.42 m long scintillating fibres with a diameter of 250 µm, readout by silicon photo-multipliers (SiPM). The fibres are arranged in mats of 6 fibre-layers with a width of 130.65 mm. Eight fibre mats will form a module and are sandwiched between honeycomb and carbon fibre composite panels to provide stability and support over the module length of 4.85 m. The modules are supported by a C-Frame structure that provide the proper stiffness to the full package. The C-Frames are also used to support electronic boards, cooling systems and services and must fit in the existing bridge/platform structure imposing tight space constraints.

One of the main purposes of the C-Frame supporting structure is to provide the proper stability during the data acquisition, but also during installation and detector opening/closing operations. To meet this goal, the supporting structure must be stiff enough to avoid unacceptable deformations and movements if subjected to variable loads. Furthermore, the fixation of the system has to be properly defined. Two principal studies have been carried out to optimize the design and the structural behaviour of the structure: kinematic and structural finite element. A detailed kinematic analysis allowed to define and optimize the proper constraints of the system during the insertion, the opening and closing phase and the service position. The theoretical fixation concept has been slightly adjusted to guarantee the proper mechanical properties in terms of stability to the supporting structure. Finite element analyses have been performed to assess the mechanical behaviours and stability for different load and constraint configurations.

A comparison with a real scale prototype, that will be assembled at CERN in April 2018, will be provided. Modifications suggested from the comparison and lessons learned will be also reported.

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The prototype of the gas system for the TOF-MPD

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The Multi-Purpose Detector (MPD) being currently developed in the Laboratory of High Energy Physics of the Joint Institute for Nuclear Research will be used for studies of hot and dense nuclear matter, by detecting particles produced in heavy ion collisions. One of the most important systems of the MPD, which will be used in the identification of these particles is Time-of-Flight (ToF) detector. It has to provide time resolution better than 100ps for effective separation of charged hadrons, so detector based on the multi-gap Resistive Plate Chambers technology, filled with gas and working in the avalanche mode has been chosen to achieve this requirement. Parameters of gas environment inside of the detector chambers have major influence on its registration possibilities. That is why ensuring suitable, clean and stable gas mixture is crucial for proper functioning of the detector.
During the presentation a prototype of the gas system for Time of Flight detector will be shown.

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Calibrated orifices for CO2 cooled detectors

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Calibrated orifices for CO2 cooled detectors

Several detectors use evaporating CO2 cooling systems. For a tracker that dissipates power and needs to mantain the sensors below a maximum temperature, i.e. -5 ℃, to avoid the thermal runaway, a CO2 cooling system integrated in the local support minimizes the total mass. This means larger radiation length.

The evaporating CO2 coolant extracts the power, dissipated mainly by the red-out front-end ASICs, changing phase from liquid to vapour, at a nearly constant temperature; saturation temperature drops along the cooling channel in relation to the fluid pressure drop. The detector temperature uniformity, i.e. 5 ℃, is controlled by its channel pressure drop. Sometime in the design small diameter pipes and non conventional geometries are used, i.e. serpentines, 2 mm inner diameter titanium cooling pipe. Analytical calculations are difficult whwn few or no correlations are available for these design typologies.
This is a first reason to investigate and set up experimentally measurements of detector thermo-hydraulic dummies.

Another reason is that the detector cooling systems fequently have parallel evaporating channels. Attention must be payd to the stability of the cooling system. The cooling distribution needs to implement proper pressure drops at the inlet of the parallel evaporating channels . To select the correct figure the cooling channel pressure drop need to be estimated.

Finally, the inlet pressure drop to be installed has to be designed and experimentally checked. There are typically two options: distributed or concentrated pressure drops.
The first one uses capillary pipes, that could be long and need to be coiled to reduce the needed space; the second one uses calibrated orifices, less common in the actual detector design.

In Milano, investigations have been conducted, and are in progress, using a TRACI CO2 cooling unit, focusing on the use of orifices for the CO2 distribution.

The actual work is dedicated to both the LHCb UT tracker and the ATLAS ITk Pixel Encap, but the measurements and outcomes can be useful for any other CO2 cooled system.

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New CERN CO2 test facility for mini- and micro-channels

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The benefits of the thermal management of tracking detectors through CO₂ boiling flows in evaporators of small diameter have been successfully demonstrated multiple times within the research community.
However, the current predictive models for two-phase flows have a wide range of accuracy, in particular when dealing with micro-channels. Due to the lack of reliable experimental data, the difficulty faced by the designer of new evaporators based on channels of very small size is even more critical when CO₂ is the planned refrigerant. There is indeed no agreement, even in the most advanced available literature, on the definition of the dimensional limits of macro-, mini- and micro scale dominated phenomena.
A long-term study has been launched with the ambitious objective of developing a deeper understanding of the properties of boiling flows of CO₂ in view of their actual application in

simple small diameter tubular evaporators as well as in complex silicon-substrate multi-microchannel cooling devices. Only a thorough and basic understanding of the physical processes occurring in mini- and micro-channels can help to optimize the design parameters of future applications.
A new test stand has been designed for testing mini- and micro-channel cooling with boiling CO₂ with an unprecedented level of accuracy. A purpose-built test circuit is housed in a vacuum vessel to guarantee adiabatic test conditions. In combination with this test circuit, a recently developed refrigeration loop for CO₂ investigations can deliver stably controlled flows at saturation temperatures ranging from -25˚C to +20˚C. High precision sensors account for pressure drop, heat transfer and mass flow rate within and along the tested tubes. Efforts were undertaken to achieve an outstanding accuracy level within the field of research. RTD sensors (Pt100), calibrated to measure within an uncertainty of 0.015˚C, provide direct measurements of the fluid temperature before and after the test section, while point-like K-type thermocouples measure the outer wall temperature of the test section with an uncertainty of 0.1˚C. A high-end differential pressure sensor in combination with a highly accurate read-out system can measure pressure drops along the tubes within an uncertainty of 1.5 mbar for a maximum of 3 bar diff. The installed mass flow meter can measure flow rates from 0.16 down to 0.003 g/s with an accuracy of 0.2 % of reading. Stainless steel tubing ranging from 2.15 mm to 0.13 mm will be tested with mass fluxes ranging from 200 to 1200 kg/m2s and heat fluxes from 5 to 50 kW/m². As a subsequent step multi-micro channels explicitly designed for possible use in tracking detectors will be tested to quantify the expected high thermal figure of merit of these devices compared to conventional detector cooling methods.
First results of pressure drop and heat transfer coefficient will be discussed in detail and compared with forecasts from existing correlations, as an essential step towards new and more reliable models for boiling flows of CO₂ in mini- and micro-channels and towards more efficient detector cooling.

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Transient Simulations of Two-Phase Accumulator Controlled Loops

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The challenges involved in cooling Silicon trackers are well known: a radioactive operating environment, tight space and mass constraints, a need for small thermal gradients and difficulty in access to the detector zone for maintenance. Two-Phase Accumulator Controlled Loop (2PACL) based systems have proven to be successful in meeting these challenges and have thus far been used on the LHCb VELO, the ATLAS IBL tracker as well as the CMS Pixel detectors, aside from the tracker on the AMS experiment of the International Space Station.

This success has led to a growing interest in such systems, and many of the next generation of tracker detectors will adopt the 2PACL cycle for Silicon cooling. These new systems, however, have much more stringent requirements: even lower detector temperatures (<-30℃); an order of magnitude greater cooling loads (in the region of 200 kW); the need to operate several plants in parallel; even smaller cooling tubes; and the need for redundancy to deal with plant failures or maintenance.

These challenges cannot be met by the existing systems without a thorough reexamination of the system design and control philosophy. The larger volumes of the detectors to be cooled, for instance, would require impractically large accumulator vessels, and underground storage of such a large amount of CO2 will present safety challenges.

To investigate alternative solutions, in addition to targeted experimental programmes, there is a need to develop a simulation tool capable of predicting 2PACL system behavior under a variety of steady state and transient conditions. Such a tool will enable designers to iterate through several design options and investigate the impact of different control strategies in a safe environment. It will also lead to savings in both time and money when compared to developing a dedicated prototype unit for each alternative.

The current work discusses the development of such a tool. A component-based framework has been developed in the object-oriented physical modelling platform EcosimPro. The platform has been previously used at CERN to successfully conduct dynamic simulations of cryogenic systems. The finite volume method has been used to discretize the governing conservation equations. Two-phase flow, which is of significant importance in the current application, has been pragmatically modeled using slip -ratio based void-fraction correlations.

A dedicated test facility reproducing the 2PACL architecture and specifically equipped for the current project has been used to collect data in a variety of transient conditions: system startup, step change of temperature set point, step change of the cooling load and finally, system shutdown. These conditions have been simulated using the component-based modeling framework presented here, and preliminary verification and validation results are discussed in what follows.

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Module mechanics R&D for phase II upgrade of CMS outer tracker

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The CMS experiment will change it's silicon tracker completely during phase II upgrade. There is need to develop light and high precision and durable mechanical structure for silicon sensor. The prime purpose of this should also be reducing material in the silicon tracker detector. The group at IIT Madras is heavily involved in R&D of production of this precision components. We have produced high precision bridge made of AL-CF material and carbon fiber stiffener.

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CERN EP R&D initiative - Detector Mechanics

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The CERN EP department has recently launched a process in view of starting in 2020 an R&D programme on new Detector Technologies. Detector Mechanics is one of the main themes within which the specific and focused R&D activities are planned to be. The current target is to provide by November 2018 a report summarizing the R&D programme proposal. We will describe the on-going process of this R&D programme launch, which topics are being considered for the Detector Mechanics R&D and explain how parties, also from outside from CERN EP, may contribute. More information on the R&D initiative is available in https://ep-dep.web.cern.ch/rd-experimental-technologies and on the Detector Mechanics working group in https://espace.cern.ch/ep-rdet-wg4-mech.

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Pipe joining techniques for Phase 2 upgrades high-pressure systems - Summary report from CERN's 18th of May 2018 workshop

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A one-day workshop about pipe joining techniques for high pressure cooling systems (including fittings, welded/brazed joints and special connections involving electrical breaks) has been held at CERN on the 18th of May 2018 with the aim of bringing together all the people working on these subjects for the Phase 2 upgrades projects and trigger discussions, synergies and possible collaborations.
In this talk I will highlight the challenges of the phase 2 upgrades in terms of joining techniques and summarize what was presented during the workshop.

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Automating the assembly of PS modules for the CMS Phase II Tracker

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For the start of the High-Luminosity phase of the LHC, the CMS tracker will be replaced by a new tracking detector; this and other upgrades will allow the experiment to both cope with the increased instantaneous luminosity and, at the same time, enhance its overall physics reach.

A key aspect of the upgraded CMS tracker is the use of double-sided pixel-strip (PS) and strip-strip (2S) modules capable of local stub reconstruction. This new hardware capability will be exploited to identify stubs from high-pT charged particles and transmit tracking information to the L1 trigger for every LHC bunch crossing. The need to correlate hits across the two sensors of a module for local stub reconstruction leads to stringent requirements on their relative alignment; for example, the two sensors of a PS module must be assembled to a relative rotational alignment of 800 microradians.

We present a method to partially automate the assembly of PS modules for the CMS Phase II Tracker. The method is based on the integration of a high-precision motion stage with a vacuum handling tool and a high-definition camera, all controlled via a dedicated software interface. The positions of the two sensors are deduced using a pattern recognition algorithm on images acquired by the camera and, based on these measurements, the two sensors are brought into alignment for the module assembly. The current status of the automated assembly procedure is discussed, including results on the first mechanical prototypes.

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Module Prototyping for the Phase II Upgrade of the CMS Outer Tracker

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To cope with the challenges of the HL-LHC the tracker of the CMS detector will be replaced by an enhanced version within the Phase-II Upgrade until 2026. The future outer tracker consists of ˜13000 double-sided silicon sensor modules of two types (2S-Modules: strip/strip sensor, PS-Modules: pixel/strip sensor) with different granularities depending on their distance to the interaction point. With readout chips connected to both sensors these so called p_T-modules distinguish charged particles according to their bent trajectory in the magnetic field by a coincidence logic. The information of high-p_T particle tracks contributes to the Level 1 trigger. The large number of modules and their complex structure puts strict requirements on various aspects of the assembly and test procedures during the production phase beginning in 2021. The various assembly and test concepts for this large scale production in respect to the 2S-Module including existing prototypes are presented.

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Wirebond Encapsulation for HL-LHC Tracking Detectors

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Silicon-based tracking detectors are made possible by semiconductor industry advances, including high-density wirebonding for interconnects. Wirebond connections are made by ultrasonically bonding aluminium wire between sensors, front-end amplifiers and hybrid circuits. A large number of low mass, compact hybrid circuit 'modules', with millions of wirebonds, are needed and must withstand the harsh operational and environmental conditions of the HL-LHC experiments. Exposure to moisture, ionic (halogen) contaminants, and mechanical/thermal stresses can be highly detrimental and have led to unexpected wirebond failures in past and recent large-scale silicon detectors. For improved reliability, I will talk about ongoing evaluations of materials and methods for protection of wirebonds from the HL-LHC environment, as well as providing for handling, assembly, electrical and thermal considerations.

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The Mu3e ultra-low-mass tracker

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The Mu3e experiment uses an ultra-low mass tracking and timing detector to search for the very rare decay $^+ \rightarrow e^+e^-e^+$. The tracks to be observed in this experiment will have a maximum momentum of about 53 MeV, hence the need for very thin detectors. The silicon pixel detector is in a barrel shape and the physics performance requires for a material budget per layer of about 0.1 % x/X_0. The pixel sensor is a monolithic HV-CMOS design which allows them to be thinned down to 50 µm. The high-density interconnect (HDI) is a flex circuit made with aluminium as conductor. The chip produces about 250 mW/cm^2 heat, which is cooled away by gaseous helium. All this will be integrated with two compact timing trackers (scintillating fibres and tiles) inside a 1 T magnetic field.

This talk will focus on the many mechanical challenges this detector design offers. After an overview, the main parts will be presented and what solutions for the mechanics have been found to meet the

requirements. The current detector design integrates all parts (electronics, mechanics, cooling and power supplies) and is currently being built as a full mock-up. Unorthodox choices were required to reduce the material, including polyimide carrying structures (25 μm thin) with integrated helium cooling channels, the use of 3d-printed structures for the gas distribution, conductively cooled copper rods for powering, to just highlight a few unique solutions developed. A strong emphasis has been put on simulation of critical components and concepts. They were compared to measurements in the laboratory using representative mock-up parts of the pixel modules and components of the Helium cooling.

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Services Design for the CMS Phase II Inner Tracker

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To cope with High Luminosity LHC data taking conditions, the CMS Inner Tracker will be rebuilt for Phase II Upgrades. To limit particle occupancy at the per mille level and improve track resolution, we will increase the granularity of the sensors. This comes with a host of challenges for routing the cooling and electrical services, and optical cabling in the Inner Tracker, especially through the Service Cylinder connecting the Tracker Forward Pixel Detector (TFPX) and the Tracker Endcap Pixel Detector. We describe our solutions to these challenges. We also describe a "cartridge system" within the TFPX that will speed up installation and maintenance. Further, we describe a structural scheme that allows easy replacement of the inner sensor layers that will be most subject to radiation damage.

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Thermo-mechanical characterization of Petals as Local Support Structures for the ATLAS ITk Strip Detector

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The ATLAS Inner Tracker (ITk) is the phase-II upgrade of the current ATLAS tracking detector, meant to meet the challenges at the high-luminosity LHC.

The forward regions of the ITk silicon strip tracker (the "end-caps") will consist of six disks populated with wedge-shaped silicon micro-strip sensors, divided in "module" units containing the readout, power and control electronics.
The modules are directly glued on likewise wedge-shaped local support structures called petal cores, consisting of carbon fiber-based sandwich structures with embedded titanium cooling pipes as well as data and power buses. These support structures with 18 sensor modules in six different shapes glued on it are called petal. Each end-cap disk will be constituted of 32 petals.
The petal core structure provides mechanical stability for the glued on sensor modules while minimizing the amount of material. Evaporative CO2 cooling is used to allow for cooling of the sensors as well as the readout electronics.

A number of prototype petal cores have been constructed at DESY and IFIC. A variant of the process has been industrialised and additional prototypes have been produced to test the alternative to the baseline design. In addition, a thermo-mechanical petal prototype, fully loaded with dummy silicon modules emulating the heat sources of the real petals with the same geometry.
A whole set of measurements has been performed on these objects to validate the petal design. This extensive prototype testing consists of measurements to address their mechanical stability (e.g. bending and vibration tests), their thermo-mechanical behaviour using dual-phase CO2 cooling (e.g. infrared thermography) and their material properties (e.g. material budget measurements).
The experimental results have also been used to validate existing thermo-mechanical FEA simulations. The aim of this process is to validate a petal design as well as planning of QA and QC concepts for production.

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Prototyping and Assembly for the CMS Phase II Tracker TEDD

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For the high-luminosity LHC (HL-LHC), CMS will install a completely new silicon tracker. Due to the anticipated increase in instantaneous luminosity by a factor of five compared to the LHC design value, the granularity will be significantly increased in order to cope with the higher track density. In addition, the tracker will provide information the first level trigger of CMS. The future tracker will consist of two barrel parts and two end caps (TEDD), one on each side. One end cap is made of five double-disks, each equipped with detector modules on all four faces to ensure a complete coverage. The backbone of the mechanical structure of the end caps are highly integrated half-disks. The contribution will give an introduction into the design of the TEDD and the half-disks, outline the status of the ongoing prototyping and R&D for the half-disks, and discuss possible assembly sequences and toolings to build double-disks and the final end caps.

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Module Design and Development for LHCb VELO Upgrade Project

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TLHCb experiment is about to implement a major upgrade, scheduled to start data taking in LHC Run III. The Vertex Locator (VELO) is the silicon detector surrounding the interaction region. It will be completely replaced with a new light weight pixel detector capable of 40 MHz readout.

The upgraded VELO modules will each host 4 silicon hybrid pixel tiles, each read out by 3 VeloPix ASICs. The silicon sensors must withstand an integrated fluence of up to $8\times10^{15} 1 MeV n_e q/cm^2$, a roughly equivalent dose of 400 MRad. The highest occupancy ASICs will have pixel hit rates of 900 Mhit/s and produce an output data rate of over 15 Gbit/s, with a total rate of 1.6 Tbit/s anticipated for the whole detector. The detectors are located in vacuum, separated from the beam vacuum by a thin custom made foil. The foil will be manufactured through a novel milling process and possibly thinned further by chemical etching.

The VELO upgrade modules are composed of the detector assemblies and electronics hybrid circuits mounted onto a cooling substrate, which is composed of thin silicon plates with embedded micro-channels that allow the circulation of bi-phase CO_2. The front-end hybrid hosts the VeloPix ASICs and a GBTx ASIC for control and communication. The hybrid is linked to the opto-and-power board (OPB) by 60 cm electrical data tapes running at 5 Gb/s. The tapes must be vacuum compatible and radiation hard and are required to have enough flexibility to allow the VELO to retract during LHC beam injection.
The entire assembly must respect
strict deformation and bending constraints, have a high radiation tolerance and very low outgassing levels. The module design will be described

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R&D on CO2 cooling using a silicon Microchannel substrate for the LHCb VELO

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LHCb is a flavour physics detector at the LHC, designed to detect decays of b- and c-hadrons for the study of CP violation and rare decays. At the end of Run-II the experiment will implement a major upgrade. The hardware trigger will be removed and the entire experiment will operate at 40 MHz. The Vertex Locator (VELO) is the silicon detector surrounding the interaction region, responsible for reconstructing the primary collision points and secondary decay vertices of long-lived particles. It will be replaced with a new light weight pixel detector equipped with electronics capable of providing 40 MHz readout.

The upgraded VELO modules will each host 4 silicon hybrid pixel tiles, each read out by 3 VeloPix ASICs with a total power consumption of up to 30 W. The tiles will be subjected to significant
radiation damage and an efficient lightweight cooling solution is essential to control reverse annealing in the silicon sensors. The solution adopted is to mount the tiles on a cooling substrate composed of thin silicon plates with embedded micro-channels that allow the circulation of evaporative CO_2. This solution is highly efficient, has low and uniform mass, and is radiation hard. Specific R/&D has resulted in a design which gives the correct pressure-flow performance and allows the attachement of the connector to the cooling substrate. The design has undergone robustness and stability tests guaranteeing that the system level performance will function correctly. The microchannels are currently in production and the cooling status will be described.

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Analytic thermoelectric modeling of the ATLAS ITk strips detector

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The thermal properties of a silicon detector are typically modeled using numerical methods, such as finite element analysis (FEA) simulation, to determine thermal performance and estimate the risk of thermal runaway. Such methods are essential for understanding detector performance, however they have some limitations: a FEA simulation can only provide results for a discrete set of operating conditions, and the process is computationally expensive.

A simple analytic model has been developed to complement the FEA approach. This model predicts the behavior of a silicon detector by calculating the cumulative effects of the thermal and electrical characteristics of the on-module detector components. A module's thermal behavior is represented by a simple network of one-dimensional thermal pathways whose properties are taken from FEA simulation. The thermal and electrical properties of front-end electronics are encoded in the model using parameterizations of direct measurements. Using this model, the performance of a detector can be evaluated over a range of operational conditions. The full lifetime of the detector can be simulated by adding the effects of radiation damage and other time-dependent processes.

We present a working example of the analytic model as applied to the ATLAS ITk strip detector in preparation for the Phase-II Upgrade. The model is used to test design choices, validate specifications, and predict the total power of the strip barrel and endcap subsystems. The model reveals insights into the interplay of detector elements and operational conditions in the silicon module, and it is a valuable tool for estimating the headroom remaining before reaching thermal runaway.

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Structure and Cooling for the CMS Phase II Tracker Forward Pixel Detector

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The High Luminosity LHC will reach an instantaneous luminosity of 5 x 10ˆ34 cmˆ-2 sˆ-1 with 140 to 200 pp collisions per bunch crossing and collect a total of 3 abˆ-1 of 14 TeV data. To cope with these challenging data conditions, the CMS Inner Tracker will be rebuilt for Phase II Upgrades. To limit particle occupancy to the per mille level and improve track resolution, we will increase the granularity of the sensors. This will result in power dissipation of approximately 50 kW. For sensors to survive the radiation close to the beam pipe, we will need to maintain them around -20 C. Thus, cooling the detector will be of paramount importance. We present a vision for the structural support and cooling services of the Tracker Forward Pixel Detector that has been studied through finite element analyses. The simulations are informed by experimental measurements of the thermal transport properties of bulk and interface materials performed in novel, custom-made apparatuses. We also present progress with fabrication of prototypes for some of the structural parts, and plans for the rest.

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Heat Transfer Interface to Graphitic Foam

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Thermal interface materials (TIMs) used for bonding components are important for creating a thermal conductive path which improves heat dissipation. Low density, porous carbon foams are commonly used for thermal management applications and devices. Their high surface area to volume ratio enables cooling more effectively via different heat transfer methods. Many studies have adopted different methods to analytically or computationally analyze the effective thermal conductivity of carbon foams. Others have studied the participation of TIMs used in composite materials. However, very few studies have analyzed the microscale effects of the interaction between TIM and carbon foams. The amount of contact between a carbon foam and a bonded surface has hardly been reported in the literature. In this study, a glassy graphitic foam developed by AllComp Inc. was used as a precursor. Graphene's highly anisotropic thermal properties result in high thermal conductivity in the planar direction, while low in the normal direction. With these anisotropic thermal characteristics, it is interesting to determine how varying TIM thickness optimizes for thermal conductivity. It is hypothesized that the direction where heat enters the graphitic foam and the size of the cross-sectional area normal to the heat flux direction would affect the overall effective thermal conductivity. Furthermore, a gap created between ligands and the bonded surface would likely reduce it. A computational model using ANSYS finite element program was developed in this study. Incorporating TIMs in the finite element model, the effective thermal conductivity is found to increase by 2.9% to 20% depending on the filler types and its thickness. With ligands at the interface removed, the effective thermal conductivity decreases by -8.5% to -40%. The results demonstrate that the parameters at the interface can be optimized to improve the overall effective thermal conductivity of the interface.

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Design and test plans of vacuum insulated transfer lines for the CO2 cooling systems of the phase II CMS detectors

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The CMS Phase II upgrade program includes a new tracker, new timing layer detectors and high-granularity silicon-based calorimeter in the endcap region. All these detectors will be cooled with liquid pumped CO2. Besides the development of a cooling system with capacity for this order-of-magnitude increase in power over Phase I heritage, significant efforts are required to define the coolant distribution from the plants in USC55 to on-detector evaporator loops.
This poster describes ongoing activities to design the vacuum-insulated transfer lines routing coolant from the plants in USC55 to the sub-detector manifolds. These transfer lines must interface with both the on-detector cooling hardware and the plants in USC55, while respecting challenging integration constraints. Moreover, the transfer lines'decisive impact on return line pressure drops and system volume makes them a major driver of cooling system performance and cost.
The present study first formulated a grouping of cooling plants, manifolds and sub-detectors to respect operational requirements and integration constraints. Based on simulations of return-line pressure drops and system volume, optimal transfer line routings will then be proposed, with on-site verification of the routing foreseen during LS2. Planned research activities concerning vacuum

insulation performance and 2-phase flow in flexible hoses and long vertical transfer lines are also presented.

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Mono-block Approach for a Refrigeration Technical Application (MARTA) –a cooling system based on the CO2 I-2PACL technology

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In the context of its High Energy Physics related activities, CERN in collaboration with NIKHEF has developed the Transportable Refrigeration Apparatus for CO2 Investigation (TRACI).
TRACI is an evaporative CO2 cooling system for scientific and industrial R&D equipment based on I-2PACL (Integrated 2 Phase Accumulator Controlled Loop) technology. The I-2PACL is the method that can instantly control the evaporative conditions in an experimental set-up vary from room temperature down to -35 °C. This technology is therefore an ideal way of controlling set-ups with a high demand on thermal stability and flexibility with a minimum of added hardware.
Cracow University of Technology (CUT) in collaboration with industrial partners: PONAR Wadowice S.A. and CEBEA Bochnia have undertaken mission of production and development of a new cooling system MARTA (Monoblock Approach for a Refrigeration Technical Application) based on TRACI. In the MARTA project there have been some new technologies applied and tested, eg. a mono-block concept, new dedicated CO2 valves. Moreover optimization has been made in power consumption, applicable range of temperature and control system. MARTA offers many optional features in order to make it more user friendly and easily operated. The coolers MARTA are characterized by significantly higher cooling capacity (up to 350W) in comparison to TRACI.
In the presentation the new enhanced system MARTA, based on monoblock concept will be shown, as well as experience and lessons learned during development, production and operation of the system. A feedback from first MARTA users is expected and it will be discussed.

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Quality Assurance and Quality Control of silicon cooling plates with embedded microchannels

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The Detector Technologies (DT) group at CERN is actively investigating the potential application of silicon micro-devices in High Energy Physics (HEP) experiments. In particular, an important effort currently focuses on the use of micro-channels etched in single crystal silicon (ScSi) wafers to circulate a cooling fluid for the thermal management of silicon detectors. However, the anisotropic and brittle nature of ScSi makes it very difficult to predict its response to mechanical loads which may lead to catastrophic failure. The DT group is conducting an extensive R&D programme in order to gain a better understanding of the behaviour of ScSi devices subjected to internal pressure. The results of this research will help to optimise the design of future devices and establish suitable quality control procedures for the production of such cooling plates.

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Micro oscillating heat pipes for thermal management in high energy physics and space applications

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Thermal management represents a major challenge in both high energy physics (HEP) and space missions. Whether it is to dissipate the heat generated by readout chips and other electronic components or to extend the service life of silicon sensors, cooling has become one of the main design concerns in both fields. Furthermore, the harsh environmental conditions encountered in both outer space and HEP experiments impose severe constraints, as the cooling solutions must operate under vacuum and absorb significant radiation doses.
Continuous advances in micro-engineering have opened the door to the development of smaller and more efficient cooling devices capable of handling increasing power densities with a minimum mass penalty. In this respect, previous work carried out at CERN has focused on the use of micro-channels etched in single crystal silicon (ScSi) wafers to circulate a cooling fluid. However, whilst this technology represents an appealing solution for thermal management in detector modules, it poses a number of challenges, particularly for high fluid pressures and long staves. Among these, the brittle nature of ScSi, the lack of suitable interconnections and the difficulties for the integration, packaging and qualification of such devices hinder their application in areas where reliability is paramount.
This research project aims to address these issues, developing high conductivity, radiation hard devices that meet the requirements of HEP experiments and space missions. Attention should be paid to improve the existing solutions for interconnections while reducing their number, creating either independent cooling circuits or closed loop devices which exchange heat with secondary cooling lines. The research would not be necessarily restricted to ScSi, and flexible materials (e.g. pyrolytic graphite) could be also investigated. Both traditional micro-fabrication methods and novel additive manufacturing techniques would be combined to tackle the problem.