Forum on Tracking Detector Mechanics 2023

Wednesday, 31 May 2023 - Friday, 2 June 2023

Eberhard Karls Universität Tübingen

Book of Abstracts

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Mechanical Vibrations of the ATLAS ITk Structures Under Transportation Loads

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The main ITk structures for the ATLAS High-Luminosity LHC Upgrade consist of concentric carbon fiber cylinders, reinforced by hat stiffeners and thick flanges. These structures were manufactured in the US, and then shipped to Europe for dressing and assembly. Although very stiff when assembled, the cylinders are susceptible to large deformations under the dynamic loads occurring during transportation. In order to contain these vibrations, and avoid damages, appropriate shipping boxes were developed. Here we discuss the assumptions made on the road and air shipping loads, reviewing available standards and measurements. Numerical models were used to verify the structural integrity under the shipping loads. The vibrations during the transportation were then measured using accelerometers attached to the shipping boxes. The measured loads were compared with the numerical model results, which were found to be slightly stiffer than reality, due to the bonding assumptions between the different components. The validated model was then used to obtain a transfer function of the shipped assembly and compute the applied transportation loads. The results of this study could contribute to the safe and efficient transportation of similar structures in the future.

This work was supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, through the US Magnet Development Program.

Keywords—Transportation Loads, Carbon Fiber Structures, Tracker Detector Mechanics

Coffee Break and Poster Session / 5

The Mu2e Calorimeter: Mechanics and Cooling System

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The Mu2e experiment at Fermi National Accelerator Laboratory (Batavia, Illinois, USA) searches for the charged-lepton flavor violating neutrino-less conversion of a negative muon into an electron in the field of an aluminium nucleus. The calorimeter plays an important role to provide excellent particle identification capabilities and an online trigger filter while aiding the track reconstruction capabilities, asking for 10% energy resolution and 500 ps timing resolution for 100 Mev electrons. It consists of two disks, each one made by 674 un-doped CsI crystals, read out by two large area UV-extended SiPMs. In order to match the requirements of reliability, a fast and stable response, high resolution and radiation hardness (100 krad, 10ˆ12 n/cmˆ2) that are needed to operate inside the evacuated bore of a long solenoid (providing 1 T magnetic field) and in the presence of a really harsh radiation environment, fast and radiation hard analog and digital electronics has been developed. To support these crystals, cool down the SiPMs and support and dissipate the electronics heat power, a sophisticated mechanical and cooling system has been also designed and realized.
We describe the mechanical details, design and performances along with the assembly status of all the calorimeter components and its integration in the Mu2e Experiment.

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Mechanical Integration of the Micro Vertex Detector of the CBM Experiment

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The four planar detector stations of the CBM-MVD will operate between 5 and 20 cm downstream of the target in the moderate vacuum of the target chamber, which is placed in the center of the CBM dipole magnet with a maximum 1 T. The harsh radiation environment of up to 7×10^{13} n_{eq}/cm^2 and 5 Mrad per CBM running year poses challenging constraints not only on the dedicated CMOS pixel sensors MIMOSIS, but also on the choice of all other materials. The sensor technology requests stable sub-0 ℃ operation during run time to maintain high detection efficiency and low fake rate. The MVD will serve as a high-precision tracking device in direct proximity of the target, allowing for low-momentum tracking, primary and secondary vertexing with a precision of below 70 µm along the beam axis, background suppression in dieletron spectroscopy and, together with the following tracking detector STS, the identification of hyperons by decay topology. Hence, minimizing the material budget down to $x/X_0 \approx$ 0.3-0.5 % per station inside the acceptance is of primary interest.

The baseline detector concept relies on integrating large-area (31.15×17.25 mm^2) thinned (50 µm) silicon sensors on both sides of highly heat-conductive carrier sheets of Thermal Pyrolytic Graphite (TPG, 380 µm thick, $\lambda > 1500$ W/mK), to provide full acceptance and efficiently conduct the dissipated power to an actively cooled aluminum heat sink outside the acceptance, respectively. pCVD diamond (150 µm thick) might serve as carrier material for the first station to minimize the material budget even further for enhanced secondary vertex reconstruction precision. The heat sinks are cooled with Novec-649 and host the first stage of readout electronics, which is connected via thin flex cables ($x/X_0 \approx$ 0.06 %) to the sensors. Each of the four detector stations comprises four independent quadrants (sensors - TPG carrier - heat sink - R/O).

This contribution will present the overall detector concept, elaborating on the selection of materials and assembly procedures, based on the Technical Design Report that has been approved in 2021. In preparation of the pre-production of the detector quadrants, compiling robust and sound procedures of high-yield sensor integration and quality assessment & assurance is of primary interest in this phase of the project and first ideas will be discussed. Insights on the selection of glues and ideas to further reduce the material budget will be touched.

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Thermal Management of the CBM-FAIR's Silicon Tracking System (STS) –Concept and Demonstrators

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The Silicon Tracking System (STS) is the core tracking subdetector of the CBM experiment at the under-construction FAIR facility in Darmstadt, Germany. The STS is tasked to provide track reconstruction (> 95%) and momentum determination (< 2%) of charged particles from the beam-target interactions (Au-Au $\sqrt{s_{NN}}$ = 2.9 - 4.9 GeV). The STS comprises of 876 double-sided microstrip silicon sensors which are distributed across 8 tracking layers. The silicon sensors are mechanically held by light-weight carbon fibre ladders, whereas the front-end electronics are placed outside the physics aperture to ensure a low material budget of $0.3\% - 2\% X_0$ per layer. The silicon sensors and the front-end electronics will operate in a range of -10 $\cdots$0°C to neutralise the radiation damage caused by the non-ionising dose of 10^{14} n_{eq} (1MeV)/cm^2 accumulated during the detector's lifetime.

The first part of this contribution will describe the corresponding cooling concepts. This will include: [1] sensor cooling concept based on impinging cold air jets to remove the sensor power dissipation of 6 mW/cm^2 at -10°C, [2] sensor thermal runaway calculations and their verification by CFD simulations and, [3] CFD and thermal simulations of the 3M NOVEC 649 based electronics cooling concept tasked to eventually remove 40 kW of power dissipation.

The second part of this contribution will focus on the experimental verification of the cooling concepts. This will include: [1] the construction and commissioning of the STS thermal demonstrator, [2] characterization of the thermal enclosure properties, in terms of its leak tightness and thermal isolation and, [3] interplay between the silicon sensor and electronics cooling to converge to the optimal operational conditions.

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ATLAS ITk Pixel Outer Endcap CO2 cooling system prototype

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In preparation for the high-luminosity LHC phase, the ATLAS detector will be upgraded with a new silicon inner tracker, the ITk, relying on a cooling system based on carbon dioxide (CO2) evaporative properties.
In order to test the key aspect of the cooling, a prototype for the ITk Outer Endcap Layer 4 Half-Shell cooling system was built in Milan and tested at the CERN CO2 BabyDEMO cooling plant. The facility is able to provide a CO2 flow of 150 g/s with a temperature as low as -45 C.
The presentation will illustrate the mechanical construction of the prototype and the use of 3D-printed titanium parts. The thermal load of the detector (expected to be 1kW on the Layer 4 Half-Shell during normal operation) was also simulated. The sizing of the capillary present in the system,

required to reach the design pressure drop 8 bar_a and to trigger the CO2 evaporation, will also be discussed. The pressure and temperature sensors installed in the prototype and the data acquisition will be described: the system includes in-flow sensors for pressure and temperature (8 of each type), a DeltaBar for the capillary pressure drop measurement and the external temperature sensors for each of the 9 evaporator pipes.
The measurement performed at the BabyDEMO cooling plant, both at the nominal ATLAS operating condition and in more extreme scenarios, will be described. The system was proved to be stable under all the conditions tested, and the total pressure drop was within the 10 bar required by the system specification. The results obtained from the prototype will also be compared to thermos-fluidic simulation.

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The CMS Outer Tracker endcaps - All the tools needed

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For the high-luminosity LHC (HL-LHC), CMS will install a completely new silicon tracker. The future Outer Tracker will consist of two barrel parts and two endcaps (TEDD), one on each end. One TEDD is made of five double-disks (DD). One DD is assembled from four half disks (Dees) with a diameter of 2.2 m. This contribution will describe the entire process from integrating modules onto Dees, assembly of DDs, TEDD integration and the final insertion into the tracker support tube (TST). Many technical challenges had to be overcome to allow for an integration that maintains a totally stress-free handling of the detector parts and guarantee high precision positioning.

A key element of the integration tooling is the so-called Arc Frame, which holds one Dee during the entire integration procedure without exerting mechanical stress to the Dee. It interfaces to the different integration, assembly, storage and transport toolings. Four Arc Frames can be combined to a double-ring during the DD assembly, while maintaining high precision and minimal mechanical stress. The various challenges to achieve this, its final design and the verification of its suitability will be presented.

The Dee integration and DD assembly toolings have been finalized recently. Both have been verified with prototype or mechanical dummy Dees. The final design features will be presented. The integration testing of prototype detector modules to prototype Dees is ongoing. The requirements for appropriate grounding places additional requirements on the Dee mechanics. Electrical connections of Al inserts to carbon fiber face sheets and the surface preparation of the carbon fiber to allow an electrical spring finger to make contact have to be foreseen now. Key results from the integration and assembly testing will be presented.

For the TEDD integration, all five DDs have to be aligned to each other for which a tooling design has been made. It uses custom designed linear X/Y/Z stages, which recently have been delivered. After alignment the global mechanics components are attached to the DDs. In order to install the global services, the TEDD will be transferred to a rotation tool, allowing to rotate the TEDD around its central axis. An axle will be inserted into the inner bore of the detector, with pneumatic cylinders pressing on inserts located at the inner radii of the Dees. Each of the 46 cylinders will be equipped with load cells to configure the pressure and monitor the load transfer. This rotation tool has now been designed and a prototype including load testing systems is under construction. An in depth look at the tooling designs will be given.

The final challenge that needs to be addressed is the interplay of all the tooling. Considering the transport of detector parts from one integration step to the next, including storage, puts additional design constraints on each tooling. A review of the whole integration flow will be given to demonstrate that this interplay is properly taken into account.

Coffee Break and Poster Session / 11

Sustainable cooling supply for the STS detector electronics

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Due to the extensive power dissipation of electronics, the STS detector requires liquid cooling supply. As cooling agent 3M NOVEC 649 engineering fluid or perfluoro(2-methyl-3-pentanone) was chosen not only because it is characterized by low viscosity and radiation hardness, but also due to the extremely low global warming potential (GWP). To cool down the cooling agent, a refrigeration system is required, which in turn, is subject to the climate regulations as well. For this reason, the refrigeration system uses CO2 as a refrigerant. Essentially, the cooling supply system of the STS does not cause greenhouse pollution and, thus, comply with the current and future refrigeration legislation for many years ahead.

In order to verify the green cooling supply concept, a pilot cooling plant was built on the GSI campus together with the supplementary systems to deliver the coolant to the thermal demonstrator of the actual STS cooling system. The performance of the plant and the supplementary systems has been investigated after the commissioning. Project accomplishment indicators, including not foreseen challenges, has been carefully assessed. Based on the experience got from the pilot cooling supply, a final cooling supply system will be built for the STS detector.

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Services for the LHCb SciFi detector at the LHC at CERN

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The Scintillating Fibre (SciFi) Tracker is the replacement of the Outer Tracker (based on gas straw tubes) and Inner Tracker (Silicon microstrips) by a single detector technology and has been installed in LS2. The detector consists of 3 tracking stations with 4 independent planes each (X-U-V-X, stereo angle ±5°) and extends over 6 m in width and 5 m in height and has a total active surface of 340 m2. The sensitive detector consists of 2.5 m long blue emitting scintillating plastic fibers of 250 µm diameter and are arranged in a staggered close-packed geometry to 6-layer fiber mats. One end of the fiber is fitted with a mirror and the scintillation light exiting at the other end is detected by linear arrays of SiPM detectors (128 channels of 0.25 x 1.6 mm2 size).
The SiPMs need to be cooled down to -40 ℃ to reduce the single-pixel noise introduced by non-ionising radiation.
Due to space constrains, the cooling line are isolated with vacuum. To maintain the vacuum, 2 redundant pumping stations based on turbomolecular pumps are located close to the detector and protected against magnetic field by a 2-layer iron shielded case.
Each of the 12 detector segments, named C-frames due to the mechanical shape, has two Pirani vacuum gauges to monitor the pressure. The presence of ionising radiation requires detaching the readout electronics from those Pirani gauges.
To avoid condensation and frost formation inside the coldbox housing the SiPM arrays, the atmosphere inside the box must be free from humidity down to a dew point of approximately -50℃. A complete sealing of the cold boxes is practically impossible, because the boxes need to ensure direct optical contact of the SiPMs to the scintillating fibers and the passage of the SiPM signals via kapton

flex cables to the front-end electronics. The low dew point is therefore achieved by flushing a dry gas through the box. A small overpressure compensates for potential leaks and the partial pressure of water vapour, which could let humid air diffuse into the box.
Flowcells devices are installed on the outgoing line of each coldbox in order to monitor continuously the gas flow. To ensure a reliable measurement a fully redundant flow measurement has been designed based on two flow meters per outgoing line. In total 576 flowmeters signals are read through a Data Acquisition system based on a PLC and back-end multiplexing.
Based on experience from testing of the first assembled C-frames a Condensation Prevention System, CPS, was added to prevent condensation on certain external surfaces. This consist of ˜800 temperature sensors with multiplexed readout made in radiation tolerant front-end electrotonic with back-end PLC readout and a system of heating wires mounted around the SiPM coldbox and connecting bellows. An electrical current trough the heating wires ensures the temperature is well above the dew point and thereby avoids condensation on the outside of the SiPM coldbox and the connecting bellows. Based on the temperature reading, the power though the heating wires are automatically adjusted.
The full LHCb SciFi detector and all services have been assembled and installed at point 8 of the LHC. The full services system is operational and first performance result will be presented.

Plenary / 13

Impact of air cooling on mechanical stability of silicon sensors in CBM-STS

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The Silicon Tracking System (STS) is the primary tracking detector of the fixed-target heavy-ion CBM experiment at the future FAIR facility, Darmstadt. It is designed to reconstruct the trajectory of charged particles within a 1 Tm magnetic field, with the goal of achieving a momentum resolution of better than 2%. STS is comprised of 890 low-mass detector modules, utilizing double-sided silicon micro-strip sensors. These modules are distributed across 8 tracking stations, each consisting of mechanical half units that support 106 ultra-light carbon fiber structures holding the sensors.
During the detector operation in harsh radiation fields, it is expected to experience Non-Ionizing Energy Loss (NIEL) damage, which will cause the innermost sensors to dissipate up to 6 mW/cm^2 at a temperature of -10°C. To mitigate the effects of irradiation, it is critical to maintain the temperature of the silicon sensors and front-end electronics at or near -10°C during operation. To maintain this temperature the inner most sensors are planned to be cooled down using carbon-fiber perforated tube which will blow cold air on the sensors. The air flow may lead to the vibrations produced in the sensors.
This contribution aims to provide an overview on the setup designed to optimize the vibrations resulting from air cooling for fully assembled ladder for different airflows. Along with the effect of vibrations on the track-based alignment softwares and the particle tracking, thus providing the overall impact of the setup on the system's performance.

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Design and manufacturing of complex shaped service interface panel with sheet moulding compound -process

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Tracker barrel with 2S-modules (TB2S) is one of the sub-detectors of the upcoming CMS Phase-2 Tracker. It is composed of 368 ladder frames arranged in a cylindrical pattern, which each house 12 silicon sensor modules. The ladder frames are assembled in a precision gluing jig, where aluminium inserts eventually supporting the modules are glued into a surrounding frame cut and glued from carbon fiber profile. The services for the modules –electrical wires, optical fibers and the cooling piping –are routed longitudinally along the ladder frame reaching to each module. These services need to be grouped and routed towards their exits in a neat arrangement towards the outer end of each ladder, which requires a designated service interface panel in the front of the ladder. This front panel needs to provide mounting positions for the adapter of the optical naked-fanout, soldering sleeves of the cooling pipes, pre-heater connectors, and to provide a strain relief for the electrical octopus going through the front panel towards the periphery of the detector.

The physical size of the naked-fanout -adapter alone forces the front panel design to deviate from the standard C-profile basis used elsewhere in the ladder frame. Instead, a fully custom geometry had to be designed to satisfy the specific support requirements and tight space envelopes while maintaining its structural rigidity contribution to the ladder frame. To realize the resulting complex geometry from carbon fiber with feasible serial production capabilities, sheet moulding compound (SMC) -process was identified as a potential manufacturing method to be utilized. In SMC, a sheet-formed raw material blank of resin and chopped fibers is simultaneously compressed and heated in a mould, resulting the material flowing and filling up the mould cavity.

To make a prototype series utilizing this method, a mould was designed, and some temporary support features were added to the design of the moulded part. The complex shape of the mould was machined from aluminium with combination of milling and EDM-wire cutting. The mould was made from individually separatable sections to ease the demoulding of the finished part. A designated afterworks jig was built for the removal of temporary features and finishing of the moulded part.

The functionality of the front panel design was proven with mock-up studies and finally in a full-scale service fitting with a real ladder prototype. The basic structure was found to be practical, only some minor improvements were proposed to the strain relief of the electrical octopus and fixing of the pre-heater connectors. The SMC-process was successfully utilized in prototyping, and it was proven to be suitable for the front panel's use-case. During the prototyping the process parameters and procedures were tweaked, and some improvements to the mould design were identified.

Plenary / **15**

Mechanical structure of the CMS TEDD detector: FEA dimensioning, mechanical tests on prototype and comparison to simulations

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The upgraded CMS Tracker, to be installed prior to the high luminosity phase of LHC operation (HL-LHC), will require novel approaches to overcome the challenges posed by the extreme radiation environment. In addition, the tracker must remain extremely lightweight and at the same time provide an efficient cooling system (evaporative CO2).

Tracker Endcaps Double-Disk (TEDD) of CMS Outer Tracker consists of two end caps of five double-disks each supporting the silicone detection modules (L1.5m and Ø2.4m). This highly integrated equipment provides 10 full planes of detection with more than 100% coverage thanks to over 13000 silicone sensors working at cryogenic temperature.
Mechanical structure that supports this assembly is particularly challenging because it must guarantee the accurate positioning of the sensors for precise reconstruction of particles trajectories for physics issues, but also very low -and controlled- deformations to allow adjusted insertion within Outer Tracker into the CMS Experiment.
Structure must also support half a ton of TEDD services (cooling, optical fibers and data wires) while remaining at the extreme periphery of the detector (between R1087mm and R1103mm) in order to stay mostly outside volume detection, with a lightweight framework to minimize particle interaction.
All these requires a massive use of CFRP (massive or sandwich) with major effort of carbon stacking definition. Mechanical dimensioning performed with numerical simulations and FEA have oriented geometry adaptation and carbon plies optimization.

This contribution will present the studies leading to the final design of the TEDD global mechanical structure. After manufacturing a partial mock-up, metrology measurements, load tests and mechanical characterization have been performed on carbon parts, as well as on assemblies and inserts. We will describe these tests and their comparison to FEA in order to validate models and parameters used in numerical simulations.

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High precision TFPX-TBPX adjustable mechanical connection for the Phase II installation of the CMS Inner Tracker

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During LHC Phase II, the CMS tracker will be updated to increase its performance given by the higher luminosity. One of the goals of this upgrade is to cover the maximum surface and to not leave gaps around the interaction point, to increase the global performance of the detector. In order to reach it, TBPX (Tracker Barrel Pixel) design is divided into two halves, staggered layer by layer, to cover the whole area around the interaction point with sensors. Due to the high precision required for the position of the sensors, the connection between separate parts becomes critical. Indeed TBPX, the closest structure to the interaction point, is connected to TFPX (Tracker Forward Pixel), a longer system which reaches its final position sliding on rails, supporting TBPX in cantilevered way. To avoid collision between layers of different halves, a tunable connection to decouple the two structures has been realized. Such connection allows TBPX positioning with respect to a precise reference system, independently from the TFPX position.
This talk presents the design solution to manage the position and orientation regulation, the connection details to reach the proper required precision, and to solve many constraints due to lack of space, high rigidity and low mass, radiation hard and low thermal expansion materials. Furthermore, it will be explained the criteria chosen to pass from the orientation extrapolation by the measurements to the regulation estimation in order to reduce the number of adjustments needed. For such a design it was taken into account the installation procedure and environment, which affects the mounting criteria.
Also presented will be the changes done to the structures in order to implement the new connection, to facilitate the manufacturing aspect of the structure.
Finally, this connection has been realized and tested in a clean room under a measuring machine, to validate its precision. This design allows to reach manually a positioning precision below 50 microns, and an angular precision below 0.1 degrees, decreasing potential misalignment.

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CMS-Phase2 Upgrade of the Inner Tracker: TBPX service flanges

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For the HL-LHC the CMS detector requires a major upgrade, called Phase-2 Upgrade, in order to provide the necessary physics performance under the challenging conditions of high luminosity. The CMS Tracker will be entirely replaced with a new tracking system, with a substantial increase in the number of channels and an improved spatial resolution. The Tracker Barrel Pixel detector (TBPX) is the central innermost part of the Inner Tracker (IT), and it is made out of four cylindrical layers, each 400 mm long, located between 30 mm and 146.5 mm away from the beamline. The layers are composed of ladders, structural elements in carbon fiber, on which the silicon modules are positioned, supported by mechanical flanges. The flanges, allocated at the entrance of the barrel, play an essential role for the module supports position and for the services distribution.

The mechanical flanges allow for assembly of the four cylindrical layers with precise positioning of each ladder, the structural support of the modules. We have investigated different materials for the production of the mechanical flanges, evaluating standard PEEK, carbon PEEK and other innovative composite materials. Many efforts are being employed for the complex design, the feasibility study and the manufacturing process.

The flanges also support the distribution of CCA (Copper Clad Aluminum) power cables, CO2 cooling tubes, and e-links (twisted pair cables sending I/O signal to the LPGBT). A Flexible Printed Circuit (FPC) with aluminum traces has been designed to route serial powering and sensor high voltage lines to the detector modules, solving numerous problems of minimum space, bending radius and material quantity. Much effort has been spent in the design of these circuits, in compliance with the specifications in terms of power, thermal dissipation, radiation resistance and material budget. We evaluated different designs, manufacturing technologies and stratigraphies in order to obtain a circuit which respects the specifications. We are working in strong collaboration with other research institutes, several companies and CERN workshop.

The mechanical flange design allows the correct fixing of the stainless still mini-tubes, used for the module CO2 cooling, with dedicated clamps that guarantee the correct tube position during the flanges assembly procedure and provide FPC heat dissipation. The e-link routing has dedicated portions on the flange to allow easy replacement of L1-layer planned after three years of running. Due to the numerous services to be arranged in dedicated paths and compatible with the assembly procedure, specific devices have been implemented in the structure.

3D printing has proved to be an excellent solution to validate the preliminary design phase of prototypes and in the realization of jigs and tools for the numerous assembly steps. Low production cost and high production speed allowed the printing of several jigs, gluing templates, handling/assembly tools, bending masks and various mockups for the construction and the validation of the first prototypes.

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Solution for cooling of portcards for CMS Tracker Phase 2

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The faster data taking and the electronics of the overall modules that will be installed in the tracker of the CMS experiment (Phase-2 for HL-LHC) will bring to a significant increase of the dissipated power. The portcards are the electronic components devoted to the data management of the inner tracker modules. The DC-DC converter, the LpGBT processor and the VTRx (optical fiber) constitute the main components of the portcards, with a global power generated of about 2.4 Watt. A total number of 136 portcards will serve the modules for the next IT barrel pixel and they will be positioned in a very narrow space, where a significant convection of the air cannot be granted, therefore, different cooling solutions have been developed to assure reasonable temperature of the electronics. The work will show the process for the definition of an active cooling solution profiting of the cooling system already in place for the modules. Both CFD and experimental studies on a demo portcard will be the starting point to go towards the mechanical prototype for holding and cooling the portcards, studied with the thermal tests in a dedicated setup.

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Terahertz Time Domain Spectroscopy for strain mapping in composite multi-material interfaces

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The characterization of detector support materials plays a crucial role in the design and construction of future colliders such as the electron-ion collider (EIC) and the Future Circular Collider (FCC), as it is imperative to achieve a very low material budget in order to minimize unwanted background signals and enhance the precision of the measurements made by the detector. The use of terahertz time domain spectroscopy (THz-TDS) in the non-destructive evaluation of material properties and detection of internal fractures and defects demonstrates its potential as a powerful tool for material characterization. We present a study validating the correlation between the optical properties of materials and their strain state using THz-TDS for the measurement of strain and stress states in complex multimaterial structural components, such as those found in the current detector support structures being used for the High-Luminosity Phase 2 CMS upgrade project. The study demonstrates the potential of terahertz time domain spectroscopy (THz-TDS) as a powerful tool for material characterization in the design and performance simulation of detector support structures, particularly in the mapping of strain at the interface between two polymeric materials. The data generated from this technique is useful in cohesive zone modelling to accurately predict the behavior of these materials in different mechanical and thermal loading conditions. Moreover, THz-TDS's ability to non-destructively detect internal fractures and defects is demonstrated in the development and testing of detector components, such as sensors, thermal interface materials, bonding adhesives, and epoxies. These materials must withstand high-energy particle collisions, and their behavior under these

extreme conditions is crucial to the proper functioning of the detectors. THz-TDS provides a non-destructive, non-invasive, and accurate method for inspecting these visibly opaque cross-sections during long shut downs as a preventive maintenance technique.

Plenary / **20**

Prototyping and testing of the transportation strategy for a high-energy physics detector

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The "Anode Plane Assemblies"(APAs) for the high energy physics project "Deep Underground Neutrino Experiment"(DUNE), must be transported more than 6000 km by road and sea. A series of activities were carried out for the assessment and validation of the DUNE APAs and their transportation structures. The APA shipping frame (ASF) assembly supports and protects the APAs for the entire trip while facilitating their handling. The ASF is installed on wire rope absorbers (damping devices) at the base, which help to limit the transfer of dynamic inputs to the detectors. Keeping in mind the APAs'cost, fragility and importance to the DUNE project, a prototyping and testing campaign was estimated necessary to check and validate the transportation strategy and the finite element (FE) models. Preliminary FE analyses were used to assess the dynamic behaviour of the structure-absorber system, select adequate absorbers, and establish optimal positioning of the measuring equipment. The first tests highlighted a stiffer than expected response of the absorbers. The cause was identified to be the dependency of the absorber's response with the energy input. Once this behaviour identified and accounted for, very good agreement was obtained between the numerical and measured data. Finally, the information obtained from the shipment to the US has confirmed the system behaviour for a longer and less controlled trip. Thus, using a more detailed FE model the results of the dynamic analyses were validated and the transportation system was demonstrated compliant with the USA and EU regulations.

Plenary / **22**

Validation of the mechanical design of the BESIII cylindrical GEM tracker against buckling-induced deformation

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The BESIII (Beijing Spectrometer III) collaboration aims to replace the spectrometer's aging inner MDC (Multilayer Drift Chamber) with a new inner tracker based on CGEM (Cylindrical Gas Electron Multiplier) technology during the 2024 long shutdown. The new Cylindrical GEM Inner Tracker (CGEM-IT) will consist of three independent tracking layers, each with three GEM multiplication stages. Stringent overall size constraints and a limited radiation length budget require the use of advanced lightweight materials such as honeycomb, Rohacell®, Kapton® and laminated carbon fiber or fiberglass meshes for realizing the structural elements supporting cathodes and anodes of the detector. The thin GEM foils are instead floating and constitute the main point of mechanical fragility

in the design.
Two out of the three layers have already been built and are collecting data in a cosmic ray telescope setup at the Institute of High Energy Physics in Beijing. The CGEM electrodes of the third and outermost layer, with their relatively large radii, suffered from mechanical issues due to buckling that prevented the detector from functioning properly.
A possible solution was found in the introduction of PEEK spacer grids in the small gaps that separate the thin GEM electrodes. This talk describes an extensive test campaign aimed at validating the effectiveness of the grids under stresses compatible with ordinary handling. A representative mockup of the detector reinforced with PEEK grids was built, equipped with accelerometers, and subjected to a series of drop tests, each followed by a full CT scan. The contribution aims to provide both a detailed case-study and a proven methodology to investigate similar mechanical issues in analog lightweight detectors.

Coffee Break and Poster Session / 23

Performance measurements of a co-axial transfer line for 2-phase CO2 HEP detector cooling

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Phase-2 CMS particle detectors require an order-of-magnitude increase in evaporative CO2 (2PACL) cooling capacity while operating roughly 20 ℃ colder than legacy systems. This requires large coaxial transfer lines, whose performance has a non-negligible impact on detector temperature. The associated relatively low CO2 saturation temperatures (<-35 ℃), large transfer line diameters, and long routings –including about 20 m of vertical 2-phase up-flow –entail significant modelling uncertainties when relying on empirical correlations with limited validation in these ranges. We report preliminary measurements on a prototype Phase-2 CMS transfer line connected to the DEMO R&D CO2 cooling plant, and assesses the performance of 2-phase flow models used to size future CMS 2PACL cooling equipment.

Plenary / 25

The DMAPS Upgrade of the Belle II Vertex Detector

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The Super-KEKB collider will undergo a major upgrade to reach the target luminosity of 6 10ˆ35 cm-2 s-1. A long shutdown is foreseen around year 2027, which provides the opportunity to revisit significant parts of the Belle II experiment and adapt them to the expected change of the experimental conditions. In particular, a new pixelated vertex detector (VTX) is being designed to fit the upgraded interaction region. This new silicon tracker aims to be both more robust against the expected higher level of machine background and more performant in terms of precision and standalone track finding efficiency.
The VTX design presented here features an envelope close to the present one, spanning from radii of 14 mm to 135 mm. The baseline layout consists of two identical layers composing the inner part (iVTX) and three outer layers (oVTX), all arranged in a barrel-shaped geometry, with minimal material budget.
It is equipped with a dedicated DMAPS CMOS sensor named OBELIX. The latter is an approximately 2 cm x 3 cm large die designed in the TJ-180 nm technology, derived from the MONOPIX-2 sensor

originally developed for the ATLAS experiment. It is expected be submitted to foundry by late 2023. The two iVTX layers have a sensitive length of about 12 cm and are based on an "all-silicon ladder"concept. A 4-sensor wide module is cut from the processed wafer and submitted to two post-processing operations: 1.) a large size signal redistribution layer (RDL) to interconnect on top the sensors along the ladder; 2.) a selective backside 50-μm thinning.
A demonstrator, based on dummy silicon wafers, is going to be realized with a monolithic self-supporting structure to assess the concept of an all-silicon ladder.
To target a material budget of 0.1 % X0/layer, the cooling of the iVTX relies on forced convection of air, expected to be applicable given the low power density of the sensors and the limited area of the inner ladders. First simulations supporting the viability of this solution will be presented.
As for the oVTX, the target material budget is ranging from 0.3 % X0 for layer 3 up to 0.8 % X0 for the 70 cm-long ladder of the fifth (i.e. external) layer. An evolved design of the ladder concept used in the ALICE-ITS is adopted, with a light mechanical structure, supporting a liquid-cooled plate. The sensors are glued on top of this plate, with traditional Aluminum flex circuits used to distribute power/controls and for data transfer. The mechanical structure of the most challenging outer prototype ladder consists of a truss structure, obtained by assembling 3 water-jet cut layers. The mechanical and thermal characterization of the prototypes will be presented.

Plenary / **26**

Low-mass support structures with integrated services for detector systems

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Future colliders, such as the Future Circular Collider (FCC-hh/ee), muon collider (MC), or electron-Ion collider pose different demands on detector mechanics and thermal performance. A common design criteria is low support mass and optimal thermal performance to effectively cool active detectors. Depending on the physics goals the support mechanics should only have between ~0.1 to 1% X_0 (radiation length) of material budget per layer. Carbon fiber composite materials allow for the development of scalable low-mass tracking detector systems with integrated services/cooling, which allows to reduce material budget substantially while maintaining a precise and low-mass optimized manufacturing process. We report on progress towards these goals with actual prototypes, coolant pressure-tests as well as detailed finite element analysis to optimize the thermal performance and confront them with data from first physical prototypes.

Plenary / **27**

Thermo-mechanical performance of the local supports for the ATLAS ITk Pixel Outer Barrel: Experimental and Finite Element Studies

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As part of the ATLAS Phase II Upgrade, a new all-silicon tracker will replace the current Inner Detector to cope with the demands of the High Luminosity Large Hadron Collider (HL-LHC). The future Inner Tracker (ITk) will include a five-layer Pixel Detector with extended rapidity coverage. In the central section, the so-called Pixel Outer Barrel (OB) will adopt a layout configuration featuring tilted modules, which gives rise to a series of new engineering challenges calling for innovative approaches in the design of the support structures and the cooling strategy.
The mechanical design of the Outer Barrel local supports relies on two main elements, namely: (i) the module cells and (ii) the functional local supports. They have been conceived to facilitate the replacement of defective modules during the construction phase, making extensive use of advanced materials and lightweight technologies to meet the stringent performance targets.
This talk will review the design and expected thermal-mechanical performance of the Outer Barrel local supports. Detailed finite element and experimental studies have been carried out to demonstrate that the proposed design meets the detector requirements. Coupled thermal-mechanical simulations have been run to assess their stability due to small changes in the cooling temperature, power consumption and moisture content. The safety margins against thermal runaway and the maximum allowable current per pixel have been evaluated using complex thermal-electrical models. Both normal operating conditions and failure cases have been considered. In parallel, thermal and mechanical tests have been performed with partial and full-size prototypes of the local supports, using the results to increase the confidence in the numerical predictions.

Plenary / **28**

Heat Extraction through Structural Components of the CMS Phase II Tracker Forward Pixel Detector

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The CMS Inner Tracker Forward Pixel detector will be rebuilt for the instantaneous luminosity of 5 x $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and up to 200 pp collisions at the High Luminosity LHC. 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 60 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 and some structural components will also serve to extract heat.

In particular, the structural materials will include carbon foam, graphite-doped carbon fiber cured at high pressures, and diamond-doped greases and adhesives. We will present thermal conductivity measurements of these materials conducted using custom-apparatus, both before and after 1.5 Grad of radiation, and demonstrate why they are our materials of choice to mitigate thermal runaway.

Plenary / **30**

Cleaning procedure of 3D printed warm nose heat exchanger and other applications

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The warm nose heat exchanger are used to control the temperature in the ATLAS detector through CO2 liquid/2phase heat exchange without any heater in the unreachable areas of the detector. Due to the limited space, these heat exchangers are produced with 3D metal printing. A large campaign is done to study different cleaning solution in order to reduce/eliminate any powder residues. This work describes all the work done for this difficult geometry. As additive manufacturing is spreading also in other experiment, the aim of this work is to describe also the solution found in other applications.

Coffee Break and Poster Session / **31**

ATLAS BARE HALF RING OUTER ENDCAP QUALITY CONTROL. A FOCUS ON THE THERMAL CONTROL.

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The ATLAS ITk outer endcap bare half ring are made of carbon fiber and carbon foam in order to achieve a low mass detector with very good thermal performance. The supports are cooled with CO2 flowing in a titanium pipe, placed between the two carbon foam half-sandwiches composing the local support. A qualification procedure was developed to verify these supports at their base stage (i.e. before placing electronics and sensors). This first quality control step is crucial for the following assembly steps. This work presents the procedure developed and agreed between Italy and UK

A special focus is given to the thermal control system which allows to verify any detect any minor defect without the use of any heater and/or thermal contact. The measurement is indeed done by mean of a infrared thermography and this contactless solution is non-damaging for the subject under study.

Plenary / **32**

Cold Krypton system for the Phase III Upgrade of the LHC

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During the Phase III Upgrade the Large Hadron Collider (LHC) will experience radiation levels extent never achieved before. The current detector cooling system operating with CO2 and the associated mechanical supports must be upgraded as the current cooling temperature is not sufficient to prevent the phenomena of the thermal runaway of the sensors. Indeed, over the years the CO2 cooling system (2PACL) has been pushed until to its limit, represented by the refrigerant triple point (≈ -55 ℃). The new temperature levels required are in the range of -60 down to -80℃. This, together with the CERN environmental policy, has further restricted the list of potential coolants for the future detector upgrade. Among them, the noble gas Krypton stands out as promising and efficient coolant. As side-effect of its thermophysical properties, the cooling starting from ambient conditions is completely different than what occurs with CO2 thus requiring a completely new cycle starting from the gas phase down to the cold region (two-phase area). A new cooling concept has been developed based on an ejector-supported cycle which differs from a traditional ejector cooling system due to the requirements in the evaporator section such as passive expansion and flooded evaporation, as well as the supercritical phase involved during the startup.
In order to emulate the Krypton cooling concept in more attainable temperature levels typical for commercial refrigeration (≈ -30 ℃), the noble gas Xenon is proposed thanks to its warmer critical temperature (≈ 17 ℃). Numerical design of the evaporator loop, as well as dynamic modelling of the cycle startup and transcritical operation is here presented and discussed. The Xenon demonstrator is currently under construction for future testing.

Plenary / **35**

Studies on supercritical carbon dioxide as a refrigerant for future detectors

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High thermal capacities and low values of density and viscosity are some of the main characteristics of supercritical fluids. These, in combination with the nature of a supercritical fluid - a single phase fluid - make them very interesting candidates for the thermal management of High Energy Physics detectors.
For future warm detectors operating at ambient temperatures and environments characterized by low radiation levels, supercritical carbon dioxide is a great candidate. The critical point of carbon dioxide is found at approximately 74 bar and 31 °C. Above this temperature, sharp changes in the fluid density as well as in the heat capacity occur. This, combined with its intermediate nature between a gas and a liquid –while being a single-phase fluid –lead to unknown mechanisms when it comes to heat transfer. While the heat transfer coefficient of supercritical carbon dioxide is shown to be excellent near the critical point, many parameters influencing heat transfer are not yet well understood. As such, further research and development in this area is necessary to fully leverage the potential benefits of using supercritical fluids for thermal management in HEP detectors. A deeper understanding of the fundamental mechanisms can lead to the development of more accurate models and optimization techniques, enabling the design of more efficient and effective thermal management systems.
In this talk, a new system designed and developed at CERN is presented. This test setup aims to provide high precision measurements of thermal-fluidic properties of supercritical carbon dioxide in the range of temperatures of interest for possible ultra-light detectors, operating at warm temperatures.

Coffee Break and Poster Session / **36**

Temperature calibration and thermal stress tests of the Front-End Electronics of the CBM Silicon Tracking System

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Silicon Tracking System of the future heavy-ion CBM experiment has several distinctive features to manage the unprecedented beam-target interaction rate of up to 10 MHz. In order to maintain a material budget within 2 – 8%X0, while achieving sufficient granularity, spatial and timing precision, a novel integration approach was employed where the read-out electronics are placed outside of the sensitive volume, being connected to the double-sided double-metal silicon sensors through the ultra-thin micro cables. Each detector module can dissipate up to 15W of power which is extracted through the limited surface of the cooling shelf. Thus, it is crucial to design and test appropriate thermal interfaces and develop monitoring routines during the detector operation.

With this purpose, we calibrated internal thermometers of the custom-made SMX ASICs of the STS: this way, the temperature of the electronics can be monitored on-line during detector tests and operation. Calibration procedure involved series of measurements with a thermal imaging camera as a reference.

Due to the temperature changes, the front-end boards (FEBs) will experience a significant mechanical stress. By subjecting the FEBs to thermal stress, the results can help identify potential weaknesses and develop improvements to enhance the performance and reliability of FEBs in the detector conditions. During the tests, many SMX parameters were monitored, what helped to evaluate the robustness of the electronics at lower temperatures.

Plenary / **37**

3D printed pipes including sensors and heaters for thermal management systems in space and on earth

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The motivation for the development of 3D printed pipes including sensors and heaters for thermal management systems comes from the limitations and difficulties in directly monitoring and acting on fluid properties with existing methods. Sensing parameters such as pressure, temperature and flow rates of refrigerant are of utmost importance for the operation of thermal management systems, on earth and in space. Ideally, these measurements shall be performed directly in the fluid flow with sensors directly in contact with the fluid. In practice, this approach cannot always be applied due to hard-to-reach measurement areas, lack of space and limitations on the total mass of the system. Current systems use sensors either located on the outer surface of pipes or inside the pipe as additional elements, introducing additional volume, mass and cable management constraints.

CERN's thermal management systems rely on a transcritical CO2 refrigeration cycle in cascade with a CO2 mechanical pumped loop, and it involves a multi-branch system with complex distribution. Therefore, distributed sensing of local flow parameters is essential for optimizing heat exchange across the thermal circuit. However, the environments where silicon detectors are present are also characterized by strict mass and volume limitations. The use of AM-produced elements within these hydraulic systems provides the necessary freedom of design to answer these constraints, while the inclusion of embedded sensing capabilities allows for the precise monitoring of vital parameters throughout the thermal management system.

In this workshop the work of the project AHEAD: Advanced Heat Exchange Devices (part of the EC programme ATTRACT Phase 2) will be presented, which is targeting on the development of pipe segments including temperature sensors, heaters and energy harvesters directly integrated into the pipe thanks to a patented [1] design and manufacturing concept relying on advanced processes such as metal Laser Powder Bed Fusion (LPBF), Aerosol Jet Printing (AJP) of electrically conducting ink patterns as well as thin insulation layers.

1. Saudan H., Kiener L. Method for manufacturing a 3D electromechanical component having at least one embedded electrical conductor. European patent 3740382 B1, 2022-05-25.

Plenary / **38**

Services Design and Integration of the CMS Phase II Outer Tracker Endcaps (TEDDs)

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To cope with the High Luminosty LHC (HL-LHC) data taking contidions the tracker detector of the CMS will be replaced by a completely new and enhanced version within the Phase-II Upgrade. The future outer tracker consists of two barrel parts and two end caps where one end cap is made of five double-disks, each hosting the p_T modules on all four surfaces. The building block of the mechanical structure of the end caps will be half-disks (Dees). The contribution will cover the design of the services starting from the Dee level going up to TEDD level including the routing of the electrical, optical and cooling services, as well as module integration strategy and testing.

The contribution will provide details on the routing aspect of the services; how the different transverse services are routed out the Dee to their corresponding patch panels, grouped on Double Disk (DD) level, and forwarded to service channels longitudinally; their analysis and validation studies to finalize the design; the full optical & electrical chain, the material choice, and the challenges encountered will be presented. Once all modules have been integrated on a given Dee and integrated with their services, the Dee will be subjected to a series of tests in quality assurance purposes, making sure modules perform as expected, requiring active cooling of the Dees. The contribution will present the details of the testing procedure and environment with the first prototype realized and tested in Louvain.

Plenary / **39**

Experimental, Analytical and Numerical Analysis of of Insert Debonding in Carbon Fiber Structures for Particle Detectors

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The Inner Tracker detector (ITk), part of the ATLAS High-Luminosity LHC Upgrade, consists of pixel and strips sensors, held in place by rigid structures designed to ensure very high stiffness and radiation length. The main structure, designed at LBNL, consists of a 3 mm thick, 6 m long and 2 m wide carbon fiber cylinder. The critical connections of this cylinder to the external cryostat and the inner structures were tested against nominal and ultimate loads, monitoring deformations and with strain gauges and LVDTs. Good agreement was found between the measurements and the numerical models, validating the design of these interfaces in terms of stability performances. The applied load was then gradually increased up to the failure load, 4 times larger than the ultimate one. Inspection revealed that the collapse of the structure was due to the debonding of the titanium insert supporting the rollers. Analytical and numerical approaches, based on Cohesive Zone Modeling of the failed interface, were used to study the failure process. Both models predictions are very close to the measured load, showing promise for use in future detector designs.

Plenary / **41**

Welcome

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Plenary / **42**

Design, thermal, and dynamic stability analyses of the air-cooled ALICE Inner Tracking System 3

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The ALICE collaboration plans to replace the inner tracking system (ITS2) during LHC long shutdown 3 (LS3), with a completely new system, called ITS3. This new system is expected to improve the pointing resolution of tracking, especially at low transverse momentum, and significantly extend the heavy flavour physics program of the experiment. The full detector consists of two half-barrels, each containing three sensors of the size up to ˜26 cm x ˜10 cm, bent in a half cylindrical shape, spaced by 6 mm in a concentrical configuration, covering a pseudo rapidity acceptance up to ±2.5 (layer 0). The development of a wafer size MAPS sensor is based on 65 nm technology, using the stitching technique to allow for a sensor size exceeding the technologies reticle size. A sensor thickness of less than 50 um and the usage of extremely light support structures based on carbon foams and air cooling allow reducing the material budget per layer to the order of 0.05% X/X_0 in the detector active area. Additionally, the first detector layer can be placed just 1.8 cm away from the interaction point after replacing the beam pipe.
The ALICE collaboration has conducted extensive testing and simulations to optimize the design of the ITS3 system. The talk will describe the global detector integration concept, including the bending procedure of the sensors, the choice of carbon foam, in terms of material density and thermal dissipation properties, as well as the thermal and dynamic stability results on first detector prototypes.

Plenary / **43**

Interlocking modular microfluidic cooling substrate for future HEP experiments

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For future experiments, the coverage of larger surfaces with silicon trackers faces challenges related to the large number of sensors to be positioned, cooled and interconnected. A modular cooling substrate design must be adopted to access industrialised series production. Replacement of faulty sensors during their integration represents an additional design requirement. In present detectors, the sensing modules are in thermal contact with the cooling line through a thermal interface material that allows for sensor replacement. This solution has a negative effect on thermal performance and sensor resolution.
In this talk, a different approach is presented. A microfluidic cooling substrate is permanently glued at the back of the sensor, providing an integrated module that can be thoroughly tested, electrically and thermally, before the final detector integration. This solution minimises the material in front of the sensor by reducing the number of thermal interfaces. On the flip side, the challenge becomes the design of a re-workable and reliable hydraulic interconnection between the modules.
The design of the interlocking Modular microfluidic Cooling Substrate is based on embedded mini/microchannels produced by either silicon femtosecond laser engraving or polymer and ceramic additive manufacturing. The research presented here looked deeper into 3D-printed ceramic substrates as new attractive material and technology for high energy physics applications.
The proposed interconnection of the microfluidic module relies on mechanical and hydraulic interlocking fixations. The mechanical interface is based on a LEGO-like concept, while an in-plane hydraulic connection across microfluidic modules provides the sealing through a micro O-ring. Design alternatives to the baseline interconnection were also explored. Production processes and materials play a key role with respect to achievable tolerances which affect the interconnection. The ability to guarantee correct modules dis/mounting, positioning capability, and sealing was investigated for polymer and ceramic samples. In addition, fundamental aspects of ceramic microfluidic substrates, such as substrate flatness, gluing interface with the sensors and their hydraulic and thermal performances, were investigated. Finally, a real detector layout was taken as a reference to evaluate the implementation of the newly developed modular microfluidic solutions.

Plenary / 44

Closeout

Plenary / 45

Progress towards the design of Phase-2 CO2 cooling systems

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In the Phase-2 upgrade of CMS and ATLAS, the scope of CO2 detector cooling systems will expand greatly. The systems will be larger, colder, and will see an order-of-magnitude increase in cooling power. The DEMO CO2 cooling system is a full sized prototype of the cooling systems for Phase 2. We have been operating DEMO for most of 2022 and 2023. In this two-part talk, we first address DEMO results, system performance, and describe the lessons learned (both in terms of thermofluids and controls). In the second part, we cover the conceptual Design of new 2PACL systems, challenges

encountered and solutions implemented in the mechanical design of both the Plant and Accumulator.

Coffee Break and Poster Session / 46

CO2 evaporative cooling system for the LHCb UT Detector

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