Forum on Tracking Detector Mechanics 2025

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University of Bristol

Book of Abstracts

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Production of the ATLAS ITk Strip End-Cap global structures for the Phase-II LHC Upgrade

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The ATLAS ITk detector comprises multiple layers: the innermost ones are silicon pixel sensors optimized for high granularity, while the outer layers consist of silicon strip sensors tailored for precise tracking. The central part of the strip detector (Barrel) is composed of rectangular ~2.5 cm and ~5 cm long strip sensors. The forward regions of the strip tracker (End-Caps) are divided into six wheels per side, each incorporating trapezoidal sensors with varying lengths and strip pitches.
The mechanical structures of the ITk Strip End-Caps have been constructed at Nikhef,
in Amsterdam. This process, including the production of individual components, quality control, integration, and final structural checks, is extensive and challenging. The final product must meet stringent specifications and maintain its integrity during transportation to CERN for its installation.
This contribution presents the production and assembly process of the ITk Strip End-Cap global structures and discusses the most relevant quality control tests performed.

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Dipole Magnetic Field Mapping at LHCb, CERN

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This project was a critical request from the experiment's technical and scientific coordination to extend the existing magnetic field map of the LHCb Dipole Magnet, to focus beyond the central region.

The motivation for this effort stems from the fact that the magnetic field was never fully characterised when the magnet was first installed, directly impacting the accuracy of measuring particle momentum. Improving the magnetic field mapping will significantly enhance data-taking precision, contributing to more accurate physics measurements and overall experimental performance.

Working in these areas is strictly controlled, with access permitted only when absolutely necessary. The cavern is densely populated with sensitive equipment, including radioactive zones and the delicate beryllium beam pipe, making this a particularly challenging environment. With just six months to design and execute the measurement, I had to develop a solution that was safe, efficient, and entirely non-invasive, all while working within strict constraints.

The measurement process required three primary systems working in tandem:

1. Mechanical Support System –The backbone of the measurement process, providing stability, precision, and adaptability in a highly constrained environment. This required fixtures to be safe and have accurate positioning of the Hall probe while allowing for necessary adjustments in real-time. Details of the systems developed are outlined below.
2. Hall Probe Sensor System –A set of 16 highly accurate, hand-made PCB-based magnetic Hall probes for measuring the field components (x, y, and z). The design of my mechanical fixtures was heavily influenced by the constraints of these probes. I collaborated closely with the Hall probe team to ensure all services were in place and that the collected data would align with the survey team's measurements.
3. Surveying System –Equipment to accurately determine the probe's position relative to the LHCb coordinate system. The laser tracker system is not designed to operate within a magnetic field, meaning its placement had to be carefully considered. Positioning was optimised by placing the system in the VELO alcove, where concrete shielding provides some protection from the field; placed on a concrete block tower perpendicular to the detector for a stable view of the downstream region; and perpendicular to the detector again upstream the magnet. For future studies, improvements could be made by investigating shielding methods that do not interfere with laser visibility or the physical sight into the magnet.

I conducted line-of-sight studies to identify the most optimal configuration of the detectors for this study. This analysis revealed that the UT (Upstream Tracker) detector should be open and that for the plane of Sci-Fi, we should utilise the detector itself due to only 50mm of visible line of sight.

These systems needed to be entirely nonmagnetic, allow line-of-sight access for survey equipment, and be safe and easy to install without posing risks to delicate infrastructure.

Measurement Systems Developed:

Out of six intended measurement planes, I successfully implemented systems for four, while two were deemed infeasible due to access restrictions and safety concerns while the beam pipe was in place for this Year End Technical Stop (YETS). In Lond Shutdown Three (LS3), the beam pipe will be removed which is a chance to further improve this mapping.

1. Upstream Tracker (UT) Rail System: Using the parallel rails of the UT detector, I designed 3D-printed guide components that could be installed mid-rail due to access limitations at the ends. A Teflon guide allowed rotation along one axis to prevent over-constraining the system. A lightweight aluminium frame supported linear movement, with an adjustable swing arm for fine positioning of the Hall probe location. This system captured 284 data points across a 3m × 1.3m space.
2. Bosch Profile Frame and Linear Rail System: This setup measured the field inside the magnet using an aluminium linear rail and a cart system. Due to radiation constraints, no drilling or destructive modifications were allowed in the area, necessitating a clamp-based attachment method. The confined workspace and beam pipe sensitivity required a lightweight and modular design. Since I was not authorised to enter the specialised access area, the system had to be adaptable to unexpected conditions. By clamping onto the magnet's shoulder bracket, the system provided

stability while remaining easy to install and remove. This setup collected 368 points across two planes with a measurement range of approximately 0.4m × 0.5m over a 2.5m rail.

3. Sci-Fi Detector System: The largest measurement plane deployed the Sci-Fi detector's movement downstream of the magnet. Covering an area of approximately $25m^2$, this system had to be extremely lightweight and minimally invasive, with fixtures attached using only Kapton tape. The setup consisted of 3D-printed and precision-machined metallic components mounted at eight vertical positions along the 8m-high detector. Each fixture had safety lines for added security. The survey team meticulously captured 40 reference targets per movement step, allowing us to gather 174 measurement points. Due to the survey process being the slowest step, the number of points was limited by time constraints.

Collaboration and Strategy Implementation:
To achieve this level of precision, I worked closely with multiple teams, integrating their expertise and constraints into the design process:

• Survey Team: The laser tracker is not designed to function in strong magnetic fields, so we carefully positioned it in areas away from the magnet such as the VELO concrete alcove or even placing 8 4 tone concrete blocks in the cavern next to the SciFi service floor. Future improvements could focus on shielding the tracker from field interference. Additionally, I facilitated the ordering of 25 new survey targets that function within a magnetic field, increasing our total to 46 targets—an investment of 13,800 CHF. Post-processing of geometric data was required to refine the positions of the magnetic field measurements.
• EP-DT Team: Responsible for providing the Hall probes, they needed clear mounting strategies, and protection plans for delicate components. I ensured that all necessary cabling was in place, and that the hand-made PCB probes were properly positioned relative to calibration. Additionally, the team developed new scripts to conduct overnight stability checks of the magnet.
• Metrology Team: Conducted in-depth investigations into the mounting plates for the survey targets and Hall probes. This level of inspection had not been achieved in previous studies, and their work is expected to improve the overall accuracy of the measurement.
• Sci-Fi Team: Since one of the systems used their detector's movement, I worked closely with them to ensure that all technical requirements were met, and that the system could safely function without compromising the detector's alignment or operation.
• UT Detector Team: Allowed me to use their rails while ensuring the integrity of their detector and its alignment.
• Vacuum Team: Provided technical expertise and were responsible for clearing the magnet area for safety. They also played a key role in installing the inside magnet rail and Sci-Fi systems while ensuring no risks to the beam pipe.
• Scientific Collaboration with EPFL: I worked closely with Arvind from EPFL, who is investigating this data. His initial brief shaped our approach, and he adjusted his model based on mechanical and physical constraints. He conducted field visits during the test phase and is now analysing the data to update the magnetic field map.

Results and Future Impact
We successfully gathered 828 additional magnetic field data points in locations that had no previous data. These measurements will undergo corrections through CERN's metrology process, refining the 1-sigma precision of around 150 µm for origin points and providing accurate estimates of the 3mRad orientation. The goal is to update the magnetic field map before the next LHC data-taking run at the end of April. If the improved field map enhances alignment and resolution, it could significantly impact the overall precision of the LHCb experiment.

More precise points of the field map have been retrieved, and I will present the findings at the upcoming forum. The aim is to demonstrate how this work has positively affected data-taking and highlight potential avenues for further refinement in magnetic field mapping at LHCb.

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Failure Analysis and Testing of Support Rails for the ATLAS Pixel Detector

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The ATLAS HL-LHC Pixel Detector (https://atlas.cern/) will be fully integrated outside of the larger detector and inserted along carbon fiber rails. The contact between these CN60/EX-1515 rails and the PEEK sliders is a critical interface. A finite element analysis study of the contact points on support rail surfaces was conducted in order to assess the structural integrity of the support rails and sliders.

The FEA model was used to determine the stress induced in rail's composite layup when fully installed in a static position. The composite material properties were assigned to full 3D solid elements for each composite ply. The Factor of Safety (FOS) for the design was determined using the Tsai-Hill failure criteria extended to 3-dimensions where the through-thickness components were included in the failure envelope. The results indicated that the proposed rail design had a FOS below 1 indicating structural failure. Several design improvements were recommended and demonstrated to improve the Factor of Safety to approximately 1.5, thus indicating structural integrity of the revised design.

The rail prototypes were fabricated in 1-meter sections to assess the quality and ease of fabrication. The finished specimens were then subdivided into multiple samples and mechanically tested to replicate the contact indentation that the rails encounter in the application. The mechanical tests were performed up to the maximum design load to screen for mechanical failure of the specimens, as well as indentation testing up to material failure to probe the strength limits of the produced parts. Experimental findings are discussed and compared to FEA study results.

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Thermal testing for the ATLAS ITk pixel outer endcap

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The new ATLAS Inner Tracker (ITk) will replace the current tracking detector of the ATLAS detector to cope with the challenging conditions for the Phase-II upgrade of the Large Hadron Collider experiment (LHC), the so-called High Luminosity LHC (HL-LHC). The new tracking detector is an all-silicon detector, composed by a pixel and a strip system.
In the outer pixel endcap (EC) sub-system, the supports on which the silicon modules are glued are half-rings (HR) composed by a carbon fiber (CF) foam, where a CO2 cooling tube is embedded.
These HRs are mounted on large CF semi-cylinders.
For the assembly of the ECs in the integration sites, beside CO2 cooling, also convective cooling for the tests will be used, using a lower power mode configuration for the chips.
Thermal cycles of the semi-cylinders in the range of temperature the detector is expected to operate will be performed during the assembly.

In this poster the results on the HR convecting cooling performed at LNF will be shown.
Also the preliminary results on the thermal cycles of CF structures, using strain gauge and optical measurements, will be presented.

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Vibrational Study of Ultra-Light Ladders in the Mu3e Tracker

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The Mu3e experiment aims to detect the rare decay $\mu^+ \to e^+e^-e^+$. It uses an ultra-light pixel silicon tracker in order to minimise the material budget whilst obtaining a high momentum resolution. The quest to improve detector resolution, as well as the challenges of multiple scattering as a dominant source of background, has driven the development of increasingly small and lightweight silicon tracking detectors. As these structures become thinner and more delicate, previously negligible mechanical effects, such as vibration, gain new significance.

The presented research investigates the vibrational behaviour of the basic building blocks of the outer pixel tracker, known as "ladders", under conditions as close as possible to those during operation. Using capacitive sensors and soon laser interferometry, we characterise their natural frequencies. We then compare the expected root mean square displacement, due to background vibrations at the experiment site, with the resolution limit imposed by the pixel size of the MuPix pixel sensors.

Understanding and mitigating these vibrations is essential to maintaining the spatial and temporal resolution required for Mu3e's physics goals. This work aims to provide a framework for evaluating mechanical stability in future generations of ultra-thin tracking detectors, as well as to inform ongoing design considerations for the in-production outer pixel detector.

Posters / **10**

A little change with a big impact

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Each pixel module installed on the Forward Inner Tracker for the CMS Phase-2 upgrade will be readout via eLinks. These eLinks were originally routed around the modules to protect their 25 micron wire bonds, however it was discovered that a significant amount of copper could be saved if the eLink routing was optimized on the Dees. To protect the wire bonds an integration ply and module spacers were added to the mechanical design. The module factories have already been developing and testing their assembly methods for years. Adding module spacers to each module as preproduction is starting causes some challenges that will be discussed in this talk.

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Summary of the silicon sensor production quality control and performance studies for the CMS Calorimeter Upgrade for the HL-LHC

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The CMS detector at the CERN Large Hadron Collider is undergoing significant upgrades as part of the High-Luminosity LHC (HL-LHC) program. One of the key projects is the replacement of the endcap calorimeters with the High Granularity Calorimeter (HGCAL), designed to provide unprecedented spatial and energy resolution in high-radiation environments. The silicon sensors are designed to operate reliably under the extreme radiation and particle flux conditions expected during the HL-LHC era, ensuring long-term performance and durability. Due to its high granularity, HGCAL will be able to provide tracking information and will be used for track reconstruction in the CMS. In this talk, we focus on the quality control and performance validation of the silicon sensors. This includes their electrical, mechanical, and thermal properties from vendor, sensor and process quality controls. Furthermore, we show the results of radiation damage studies using test structures, full sensors, and modules, to evaluate whether the radiation hardness meets the required specifications. Additionally, we present key observations from the production phase and highlight lessons learned to enhance future sensor development and manufacturing processes as well as quality control procedures.

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High-Precision Engineering for the ATLAS Inner Tracker Outer Endcap

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The Large Hadron Collider will be upgraded to increase the machine luminosity. The ATLAS experiment has developed an all-silicon inner tracker (ITk) to operate with much higher density of tracks while improving the performance of the tracking system. To withstand this harsh high luminosity environment, both a low material budget and radiation hardness are critical.
Within the ITk pixel system, the outer endcap local supports are three differently sized double loaded half-rings. These structures provide mechanical support and cooling for the silicon pixel modules. The placement of the silicon modules and the local supports is paramount for the optimal reconstruction of the tracks of the particles produced on each collision.
These half-ring assemblies feature carbon sandwich structures and radiation-hard polymer inserts, which are hand-assembled using radiation-hard glue. The machining tolerances of the carbon composite structures are typically tighter than expected due to the material's anisotropic nature and are even tight by metallic standards. To meet the required specifications, extremely precise tooling is needed, testing the limits of CNC technologies.
Positional tolerances of hole features in assembly plates are as low as 35 µm. Achieving this requires a precisely flat surface over an area as large as 0.3 m^2. This is only achievable by using extremely stable CNC machines and software capable of compensating for environmental temperature variations. In addition to these plates, custom fixings are required, produced to fit within these hole features with a clearance of less than 10 µm.
Producing these parts is only the first stage. Next, advanced precision metrology is required to verify that the tooling has been made within these specified tolerances. A combination of mechanical, optical and laser metrology techniques is necessary for this.
After extensive iterations and skilled technical effort, we have passed the pre-production requirements for these hand-fabricated carbon sandwich structures and are now undergoing full-scale production. In this contribution, all the challenges faced during the R&D and prototyping phases that enabled us to comply with the project specifications will be presented.

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ATLAS ITk strip staves: the long and rocky road from R&D to production

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The major limitation to the performance of the current ATLAS Inner Detector is that the long radiation length severely degrades the electron energy resolution and vertex pointing accuracy. Therefore, when ATLAS was considering options for the ITk upgraded tracker for HL-LHC, the choice was determined by the radiation length budget. The lowest radiation length solution was the one in which the silicon modules are directly glued onto carbon fibre support structures (called staves for the barrel region and petals for the end caps).
The staves use a carbon fibre honeycomb structure. The electrical signals and power are provided by the "bus"tapes, which are "co-cured"to the carbon fibre skins. The cooling is provided by bi-phase CO2 in thin wall titanium pipes. After completion and QC of the mechanical staves, silicon modules are glued onto the staves and wire bonding is used to connect the modules to the bus tapes.
Many aspects of the project turned out to be more challenging than expected. The bus tapes need to transmit high speed data over 1.4 m length as well as providing low and high voltage to the modules. A custom Bus Tape Testing Robot (BTTR) was used to test for continuity, short circuits and High Voltage Insulation Resistance for the bus tapes at all stages of assembly. After co-cure of the bus tapes to the carbon fibre skins, there could be significant dimensional changes and this required custom tooling to control this. The BTTR also performed dimension measurements to check that the distortions were within the specifications.
The cooling loops use Ti pipes with a wall thickness of 160 um. The need to electrically isolate the stave from the pipes outside required the use of ceramic "electrical breaks". Orbital welding was used to connect the pipes to the electrical breaks. This gives rise to concern about the reliability under pressure. CT scans were performed which showed worrying pores but extreme QA was used to validate the process. The geometry of the pipes existing the stave had to be adjusted late in the development phase to allow for the very tight space constraints during integration into ATLAS.
The staves were assembled from the parts using precision jigs. The thermal performance was assessed by using cooling fluid and an IR camera to measure the surface temperature of the staves. This is very sensitive to any local defects in the staves.
The hardest specification to achieve was the requirement of local flatness on a stave over the area of a silicon module. This is meant to ensure that there will be glue in all the required places. However, the specifications were not carefully considered at the start and were optimised very late in pre-production. In addition, it is extremely difficult to avoid small dents in the surface, so it was agreed to repair these using Hysol.
One major issue for the ITk strip detector that emerged during pre-production was that the CTE mismatch between the Cu in the flex circuits ("hybrids") in the modules is very different to silicon. This led to cracks in the silicon sensors when the staves were cooled. A solution has been found but this led to severe delays in the project. Tests had been performed with prototype staves operated cold but the tests were not realistic.
20 pre-series staves are now being assembled and will be used in ATLAS if they pass QC. If the yield is acceptable, we will start full production after the pre-series. The most important lesson learnt is that not enough thought was given to the specifications at the start of the project. Also insufficient testing was done during the development phase so that very serious problems emerged late and caused significant delays.

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Design and Testing of the Outer Barrel Stave for the ePIC Silicon Vertex Tracker (SVT)

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The ePIC silicon vertex tracker (SVT) will feature five-barrel layers and five disks at each end. The outer barrel (OB) consists of two layers at radii of 270 mm (L3) and 420 mm (L4). All parts of the SVT must satisfy extremely low material targets, of 0.25% X0 for L3 and 0.55% X0 for L4. The SVT will utilise a reduced-size version of the MOSAIX MAPS sensor, originally developed for the ALICE ITS3 detector. These large area sensors (LAS) are thinned to 40 μm, with dimensions of 20 mm in width and either 110 mm or 130 mm in length.

Mechanically, the OB layers are segmented into staves, each two sensors wide and supporting a total of 8 sensors (L3) or 16 sensors (L4). The power consumption per stave is approximately 25 W (L3) or 50 W (L4). To minimize service material, we aim to use serial powering and air cooling. Serial powering requires an ancillary chip that generates significant heat, necessitating careful thermal management. Air cooling will primarily rely on forced airflow through the stave core.

Since the last forum, several quarter-length stave prototypes have been constructed to validate forced internal airflow cooling performance. Thermomechanical dummy modules simulate heat load from the LAS and ancillary ASIC. Experimental assessments of thermal performance, pressure loss and airflow induced vibrations were carried out to verify the accuracy of computational fluid dynamics (CFD), and Finite Element simulations. These assessments have guided the design of a full-length L4 stave, currently in production. This talk will present the updated stave design, along with results from experimental testing, mechanical and thermal finite element analysis (FEA) and CFD of the airflow in the stave core.

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Experimental Characterization of Composite Joints in MRI Magnets at CryogenicTemperatures

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A bore magnet within a magnetic resonance imaging (MRI) machine consists of coils of superconducting wire, impregnated with an epoxy resin to hold its shape and simultaneously acts as an adhesive to bond the solenoids to electrically insulating and supporting rings of glass fibre reinforced polymer (GFRP). During operation, while the magnet is maintained at 4K, the coils induce significant and complex electromagnetic forces on the inert GFRP rings. Plasma focused ion beam milling integrated with SEM enables inspection of subsurface damage in the epoxy in and around the adhesive bond post cryogenic thermal shock.

After the structural integrity of the constituent materials has been assessed, complex loading conditions can be applied to the interfacial region between the GFRP rings and the coil to examine the structure's response to representative operational loads. A modified Arcan fixture (MAF) and digital image correlation (DIC) are employed to assess the full field deformation and failure behaviour of the solenoid/GFRP joint under bi-axial stress states at cryogenic temperatures. This is possible with the use of a specially designed cryostat that isolates the specimen between the MAF clamps at temperatures down to 100K.

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Primary experimental observations indicate that the failure load and overall stiffness of the composite joints increases with decreasing temperatures. The failure load observed for composite joints cut from an MRI magnet is lower than that of a simpler bond configuration used to develop the experimental methodology. Instead of the crack being forced along the adhesive plane, as is the case for the simplified specimens, failure in the contemporary specimens can propagate into the adherends where the crack follows the path of least resistance. Partial failure envelopes for both material cases at varying temperatures are presented, with discussion into how the results can be used to inform predictive models of the whole magnet.

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Multi-Stage Structural Optimization for FCC-ee Interaction Region Support Structures

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Structural optimisation is crucial in modern engineering, especially for ambitious projects like the Future Circular Collider, a proposed 90.6 km high-luminosity electron-positron collider. This contribution focuses on designing a lightweight yet robust support structure for the interaction region, minimising material while achieving mechanical performance criteria.

A three-stage optimisation strategy was applied at both macro and micro scales. In the first stage, the interaction region's main components supporting structure was optimised using the Solid Isotropic Material with Penalisation method and generative design. Mass reductions of 76%, 73%, and 68% were achieved for two, three, and four anchoring point configurations, respectively.

The second stage refined local regions using Solid Isotropic Material with Penalisation method, generative design, and lattice-based, field-driven optimisation, achieving up to 80% mass reduction.

The third phase developed a custom lattice structure based on minimal surfaces. An iterative particle-spring dynamic model was implemented to generate the lattice while satisfying symmetry and boundary conditions. In comparison with the usual method for the minimal surface evaluation, using the Lagrangian equation, the proposed methodology allows to find the minimal surface configuration using iterative steps of equilibrium.

Throughout each phase of this study, various optimisation methods were employed to determine the most effective approach for the analysed support structure, ranging from the overall structure to the individual cell of the lattice structure.

Forum 2025 - session 2 / 20

Ultra-light geometry for the CMS Inner Tracker "phase 3" upgrade –TBPX

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This talk focuses on the current status of the design for a potential "Phase 3" upgrade of the innermost layer of the CMS Inner Tracker (TBPX). Due to the high radiation levels expected, the innermost layer of the detector will need to be replaced midway through the High-Luminosity LHC (HL-LHC) program. This necessity creates an opportunity to develop and implement improved mechanical structures and electronic systems to enhance CMS performance during the second half of the HL-LHC era.
Specifically, the talk will explore the concept and the main steps taken to adapt a geometry developed for the ALICE Inner Tracker to meet the CMS tracker's constraints, including space availability, cooling system requirements, module power dissipation and material budget targets.
Furthermore, the presentation will highlight the main challenges and potential solutions identified when applying the ALICE geometry to a CO_2-cooled detector like CMS. These aspects are still under investigation and testing: the talk will present the current proposed solutions to address them. The aim is also to open the floor for discussion and gather valuable feedback on the most promising technologies for the potential Phase 3 upgrade of the CMS Inner Tracker.

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Commissioning, Operation and Future Possibilities of the ATLAS and CMS DEMO Inheritance CO2 Cooling Systems

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The ATLAS and CMS Phase-2 detector upgrades will employ CO_2-based evaporative cooling to ensure stable thermal operation of the newly developed silicon tracker modules, which are scheduled to be installed during LS3. Extensive validation and commissioning must be completed beforehand to guarantee proper cooling performance of the detector modules. In particular, cooling loops must be verified for intended pressure drops, proper heat dissipation, and overall functionality before detectors are ready for installation.

To support this effort, two dedicated cooling plants, one for each experiment, have been constructed using a combination of inherited hardware from the DEMO system and initial set of outsourced final components. These plants, referred to as *DEMO Inheritance*, are designed to validate cooling performance of detector prototypes and final structures, but are also intended to gauge the functionality of the newly installed plant and accumulator assemblies. Additional system elements have been integrated to simplify the connection of detector modules, allow controlled filling and evacuation

of detector volumes, and enable distribution of flow and pressure to multiple prototypes simultaneously.

As these systems represent a step forward from the original demonstration plant, a commissioning campaign was carried out to ensure the operational readiness of the plant and characterize system performance. In parallel, procedures were developed and tested to streamline the commissioning for the final cooling systems, most notably the automation of component characterization, such as heating elements and pumps. Given the need to commission a total of 16 systems for Phase II, fully tested automated procedures are critical to make commissioning tractable and coherent.

This contribution will present the commissioning process of the inheritance plants, the procedures developed to support the upcoming installations, and the overall system performance and readiness. Additionally, the operator workflow and functionality will be presented as an introduction for new users to get acquainted with the cooling plants. This will serve as a basis to discuss expectations and possibilities for performance validation of the final detector modules.

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Thermomechanical analysis of the barrel electromagnetic calorimeter of the ALLEGRO full detector concept at the FCC-ee collider

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ALLEGRO is a general-purpose detector concept for an experiment at FCC-ee featuring a noble-liquid electromagnetic calorimeter (ECAL) as one of its central detectors. Noble-liquid calorimetry is a promising option for future particle physics experiments, applicable to both hadron and lepton colliders. This ECAL comprises 1536 multi-layer read-out electrodes, realised as Printed Circuit Boards, and an equal number of absorbers, all immersed in liquefied noble gas at cryogenic temperatures. The absorbers consist of metallic composites, with a lead core and a stainless-steel skin. Unlike the ATLAS experiment structure, the electrodes and absorbers in ALLEGRO are straight and inclined relative to the radial direction of the ECAL. The new design is also larger and heavier, requiring a rethinking of the assembly that supports the detection components. This work presents the thermomechanical finite element analysis of a third of the new ECAL, paying special attention to the displacements of the rings, the deflection of the absorbers, and the variation of the noble liquid gap, all at room temperature and under cryogenic conditions.

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Experimental tests on TBPX cooling loops at different CO2 vapour qualities

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This study presents experimental thermal tests on TBPX evaporators conducted at CERN, B186.
The primary objective is to validate the current design of the most critical cooling loops with an inner diameter of 1.6 millimeters and, in second instance, to evaluate the impact of vapor quality (VQ) and Heat Flux on the thermal performance and stability of the cooling circuits by examining various operating configurations.
The experiments were performed by changing the VQ levels at 40%, 33%, and 25% and analysing the circuits' behaviour at different heat fluxes.
The results reveal that significant instabilities and high temperature peaks occur at high operating heat fluxes, particularly at 40% VQ: the current design value.
However, the 33% and 25% VQ settings exhibit improved stability; specifically, the 25% VQ configuration shows a marked reduction in instabilities, while the 33% VQ setup experiences only small temperature spikes at higher heat fluxes, suggesting a promising enhancement in thermal management.
The analysis, which is built on the evaluation of averages and standard deviations for every test configuration (Heat Flux and VQ), contributes to optimize the cooling's design of CMS Inner tracker.
The findings provide a solid foundation for simulation studies (Multiline's simulations) to investigate pressure drops and to assess the feasibility of achieving the 25% and 33% VQ targets under operational conditions.

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Thermal Quality Control for the upgrade of the CMS Tracker TBPS tilted ring for the LHC High Luminosity phase

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The focus of this work is on the thermal quality control of the TBPS tilted ring structures for the future CMS tracker, which is currently under production in preparation for the Phase-2 Upgrade of the Large Hadron Collider (LHC). This upgrade aims to enhance the performance of the CMS detector, making the validation and optimization of cooling systems crucial to ensuring the proper functioning of the electronic modules that house the silicon sensors of the tracker throughout the detector's entire lifespan.
Specifically, this work provides a detailed description of the thermal test setup located at CERN in Building 186, which is connected to the CO2 cooling plant, TRACI. The TBPS tilted rings are tested weekly at the end of the production process. The work outlines the procedures followed and the key results obtained, with a particular focus on the cooling performance of the TBPS tilted ring structures under operating conditions with two-phase CO2 at -35°C. Moreover, the thermal quality control tests have enabled the detection of anomalies and the findings have contributed to improve the thermal performance of the tested rings. Additionally, the results have provided valuable and repeatable insights that enhance and validate the production process.

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Developments in the Mechanical design of the LHCb VELO Upgrade II

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The upgrade of the LHCb Vertex Locator (VELO), planned to be installed in 2033, presents a wide range of mechanical engineering challenges driven by the need for minimal material budget, high radiation tolerance, and mechanical stability under stringent operating conditions.
The detector will be composed of detector planes arranged as modules along the beam direction. Each VELO module integrates silicon sensors, readout ASICs, and lightweight support structures with embedded cooling and service interfaces.
The use of advanced materials—such as 3D-printed titanium, aluminum, and ceramics-is being explored for multifunctional substrates that offer both structural support and efficient thermal coupling. Particular attention is given to thermal expansion compatibility and adhesive properties to ensure long-term reliability under the extensive radiation requirements.
The cooling system is based on boiling CO_2 at low-temperature circulated through small channels embedded in the substrates, with ongoing R&D into sublimation-based cooling to further reduce operational temperatures while maintaining performance.
The entire detector is enclosed in a secondary vacuum volume and protected from beam-induced electromagnetic interference by an ultra-thin retractable RF shield, which operates with high precision and radiation hardness.
We consider two main detector designs which will be shown in detail in this presentation. We will also present the current status of the VELO mechanics R&D and preliminary results from tests of the cooling substrates.

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Embedding vascular networks in carbon composites for tracking detector thermal management

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High-energy physics experiments rely on high-performance tracking detectors composed of silicon sensors mounted on lightweight structures. These structures must not only provide adequate support but also incorporate a network of cooling fluid to manage the thermal load of the silicon sensors. Effective thermal regulation is critical to sensor performance, ultimately influencing the quality of experimental results. Current state-of-the-art tracking detectors utilise a network of metallic or plastic pipes containing cooling fluids. However, introducing foreign materials can lead to thermal expansion mismatches, alter mechanical properties, and impact the through-thickness radiation length of the structure. This study explores the vaporisation of sacrificial components (VaSC) as an approach to creating embedded fluid cooling networks within carbon fibre composites. By utilising sacrificial materials compatible with additive manufacturing, VaSC preform geometries were fabricated. The geometrical accuracy of the embedded network was evaluated using both invasive and non-invasive imaging techniques, demonstrating the feasibility and effectiveness of the VaSC method.

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Ultra-lightweight outer pixel tracker for the Mu3e experiment

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The Mu3e experiment is on the frontier of charged lepton flavour violating searches and seeks to observe the rare muon decay $\mu^+ \rightarrow e^+e^-e^+$, as well as paving the way globally in terms of cutting-edge ultra low-mass detector technologies. Based at the Paul Scherrer Institute (PSI), a leading Swiss national laboratory near Zurich, the Mu3e experiment consists of four pixel tracking layers, as well as scintillator fibre and tile detectors.

The Mu3e outer pixel system is defined by three identical "stations", one centred around the muon target, and one on either side known as the "recurl"stations. The central station will be built and operated first; and is scheduled to be installed in the beam area at PSI for data-taking in 2026. The basic module building block of the pixel tracker system is known as a *ladder*, which consists of between 17 and 18 70μm thick HVMAPS MuPix 11 pixel sensors in the case of the layer 3 and layer 4 (outer) pixel detector layers. In addition to the sensors, the ladders consist of an $\sim 80\mu$m thick aluminium/polyimide high-density interconnect (HDI) for the electrical connections and a mechanical support. Each of these layers are held together with minimal glue deposits, which are precisely controlled both in their placement location as well as the deposit amount. The radiation length of a 70μm Mu3e outer pixel ladder is approximately 0.1% X/X_0. This ultra-lightweight detector design is driven by the need to minimise the dominant effects of multiple scattering and to achieve precise momentum resolution of less than 1 MeV.

Electrical connections between the HDI, the sensors, and the read-out are achieved using single-point Tape Automated Bonding (spTAB). Over 1000 of these TAB bonds are required per ladder. Extensive electrical and thermo-mechanical tests have been undertaken to qualify the ladder objects as part of the QC/QA procedures before construction can commence. An innovative carbon-fibre geometry used solely for the outer pixel ladders has been custom-designed and will be presented in this talk. This mechanical support consists of 25μm uni-directional tow-spread carbon-fibre sheeting cured into a double-u shaped profile, with a 30-40% resin content and an 8μm kapton co-cured back layer for electrical isolation. The design considerations centre around the primary goal of ensuring maximum stiffness to protect the pixel sensors and improve ladder construction yield, whilst remaining extraordinarily lightweight. In total, 156 working ladders are required (52 per station), each weighing only $\sim$ 2.5 grams. The Oxford Mu3e group is responsible for producing all ladders required for the outer pixel tracking system. An overview of the ladder-building procedure will be presented, which includes a snapshot of various thermo-mechanical studies that have been undertaken on prototype ladders in the lead-up to the production phase. Experience in handling 70μm thick silicon wafers as well as the performance of the MuPix 11 pixel sensors will also be presented.

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Design, construction, electrical and thermal performance evaluation of the power cables for the Outer Tracker detector for the Phase-2 upgrade of CMS

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The Outer Tracker (OT) for the CMS phase-2 upgrade is composed by more than 13 thousand silicon detector modules. Each module is individually connected to "Low Voltage"(8 to 13 V) power for the front-end electronics and to "High Voltage"(0 to -800 V) bias for the silicon sensors, ensuring high powering granularity. Additional needed electrical services are pre-heaters for the CO2 cooling system and sensors for temperature monitoring. Custom-designed power cables bring the required electrical lines from the power supply boards, located on balconies at the sides of the CMS apparatus, to the tracker detector, following approximatively the same path as in the present detector, with the same space constraints, while ensuring higher granularity and higher power density (the OT is requiring 150 kW power, around three times the present CMS tracker detector). The design of the power cables poses exceptional challenges; innovative technologies are adopted for the different cable segments. Thin Copper Clad Aluminum (CCA) wires are used in the region inside the tracking volume, where it is essential to keep very low the material budget, one key driver of the tracking resolution. Enamelled solid Copper conductors are adopted in the region outside the detector, ensuring low resistivity of the Low Voltage lines, essential to meet the powering scheme requirements. The enamelled wires allow to optimize the conductive surface area within the available cable cross-section. The R&D done to develop these cables and their harness is reported, posing particular emphasis on the study (both via numerical simulations and through measurements in the laboratory) of the thermal aspects, which, due to the given power density, have great importance, especially in the interconnection regions.

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HL-LHC CMS Barrel Timing Layer and Tracker Support Tube: Mechanical Loading Tests, Metrology, Integration and Installation Updates

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The Barrel Timing Layer and Tracker Support Tube (BTST) is a 2.4-meter diameter, 5.3-meter long composite sandwich structure designed to provide primary mechanical support for the Barrel Timing Layer, Outer Tracker, and Inner Tracker detectors of the CMS detector for the HL-LHC. This presentation provides updates on mechanical loading tests, metrology, and simulation validations following a mock loading exercise conducted after a transportation-related road accident in June 2025. The talk also addresses findings from manufacturing quality control and addresses the next steps in the integration and installation of the BTST at CERN. Key learnings from the development of accurate material models—reflecting as-manufactured properties and realistic boundary conditions necessary to simulate worst-case loading scenarios expected during installation into the calorimeter with the temporary support structure (Eiffel tower)—are discussed. The realistic installation and integration simulation are used to establish safe operating procedures, and evaluate any potential modifications needed to external temporary supports. Additionally, the metrology techniques used for validation of the BTST, along with plans for QA/QC, will be presented. This talk serves as a follow-up to previous presentations at FTDM 2024, which covered the initial design, simulation, and manufacturing process of the BTST.

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Temperature dependent thermal conductivity measurements and their effects on the thermal management predictions for CMS TFPX Dees

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We present measurements of the temperature dependent thermal conductivities for carbon composite laminates, thermal interface material, carbon foam and adhesives used for the construction of the Tracker Forward Pixel detector support structures as designed for the HL-LHC CMS upgrade project. The simulation set up for thermal performance using temperature dependent properties is described and comparative simulation results are presented to highlight the effects of temperature dependent material properties. First efforts to measure the thermal contact resistance using Laser Flash Analysis method are presented for co-cured facesheet to carbon foam interface and titanium pipe glued to carbon foam interface.

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Novel design ideas for future particle tracking detectors

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In the pursuit of advancements in particle physics and broadening our understanding of the universe, there is a huge demand for efficient lightweight particle detectors. Low detector mass, clever integration of different functions, optimization of active detector area and optimization of thermal management in particle tracking detectors are keys for pushing the boundaries of our knowledge, as each of these perspectives helps directly to provide better data for physics.

Considering these key areas, two detector concepts are presented in this talk. Each concept will address these challenges in their own unique ways. Ultimately, combining the ideas from these concepts could be the answer for unlocking the next generation of particle detectors.

In the pursuit of efficiency and thermal optimization, a more traditional "Forward"tracking detector design is used as a basis for innovation. To achieve these goals, the focus will be in cleverly combining the services and support structures together, to form self-supporting "Mega-structures"with integrated cooling channels. In this concept, the services of the detector ultimately become part of the supporting structure of the detector itself, and no material is wasted on a single function.

To pursue improvements in the active area management and mechanical mass of a particle detector, a very novel Dyson sphere detector concept (Figure 1) is introduced. The aim is to envelope an interaction point with a particle detector constructed from multiple spherical layers of modules (Figure 2). This concept is made possible by combining foldable materials together with a clever module design that is easily scalable for creation of larger "Mega-module,""Giga-module,"and "Peta-module"assemblies to populate all layers of the detector with a single module design.

Figure 1, First two layers of the Dyson Sphere detector concept

Figure 2, Section view of the first two layers of the DSD-concept

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CO_2 Surface Storage: safety (for operation, detector, and personnel) implications on the design of the system

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The development of the CO_2 surface storage module represents a critical advancement in extending the Phase II underground cooling systems of the ATLAS and CMS experiments at CERN. Over the past two years, the design has evolved to meet complex engineering challenges associated with safely and reliably transporting liquid CO_2 underground. Central to the design is the integration of a thermosiphon system to ensure high reliability in liquid delivery, while robust safety measures allow for complete system isolation in the event of a leak, preventing the release of up to 8 tons of CO_2 in the caverns. The tank module has been engineered to accommodate various operating scenarios and withstand potential failure modes. A comprehensive redundancy strategy enhances system availability. Finally, an advanced dynamic model has been developed to carry out simulations of the tank that can capture and help us to understand the transient behaviors during insurge and outsurge events. This last development will help the future commissioning of the tank.

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Large scale production of the 2PACL cooling sub-systems

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In order to meet the challenging thermal and environmental conditions of the ATLAS and CMS upgraded detector after LS3, a next-generation CO_2 evaporative cooling system has been developed. The new infrastructure is built around a modular design, consisting of multiple independent cooling units operating in parallel. Each module includes a dedicated cooling plant and a high-pressure accumulator, both located in the respective service caverns of ATLAS and CMS. These systems are responsible for supplying cold, saturated liquid CO_2 to the detectors through a network of transfer lines and manifolds.
The liquid CO_2, maintained at temperatures as low as -54 ℃ and pressures reaching 100 bar, will circulate in a two-phase flow regime. Compared to the previous systems used at the LHC, the new setup offers increase in both cooling capacity and operational volume.
As a result, substantial design adaptations were required in the CO_2 systems and its full infrastructure. The well-established 2PACL cooling concept was scaled up, incorporating larger plant dimensions, a reimagined accumulator principle, and industrial-grade piping and manifold enlargement.

All of this required a completely different approach to the construction of the cooling systems, passing through a number of large industrial contracts, worth several MCHF. Following up on last year's presentation, which addressed the preparation for outsourced production and CE marking, this talk will serve as a complementary overview—focusing on the lessons learned during the detailed production phase of the multiple units composing this large-scale mechanical system. It will cover the challenges faced, solutions implemented, and practical experience gained throughout the manufacture and reception of multiple CO_2 cooling units, including plants, accumulators, and distribution manifolds. The experience of large-scale outsourced production, somehow usual for the serial production of detector module components, has never been faced in our environment for such large and complex systems, and provides useful indications for the design and procurement organization of large-scale infrastructural mechanical components of future experiments.

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Development of Lightweight Forward Discs for the ePIC SVT at the EIC: Mechanical and Thermal Design, Prototyping, and Testing

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Experiments at the future Electron-Ion Collider (EIC) pose stringent requirements on the tracking system for the measurement of the scattered electron and charged particles produced in the collision, as well as the position of the collision point and any decay vertices of hadrons containing heavy quarks. Monolithic Active Pixel Sensors (MAPS) offer the possibility of high granularity in combination with low power consumption and low mass, making them ideally suited for the inner tracker of the EIC detector(s). The forward discs are critical to the measurement of the scattered electron, and thus minimizing the mass is crucial.
To that end, we have developed a disc design for the ePIC Silicon Vertex Tracker (SVT) that incorporates a corrugated carbon fiber core to add strength while providing a channel for air cooling. Recent efforts have focused on prototyping discs using updated carbon composite structures and more realistic module geometries to better reflect the final detector configuration. New thermal tests incorporating updated power dissipation estimates have been conducted, and detailed finite element analysis (FEA) has been performed to model thermal behavior, with results compared directly to lab measurements. In addition, new tooling is being designed to enable precise and repeatable construction of the complex disc geometry. We have also begun mechanical stress testing to evaluate structural performance under simulated operational loads. In this talk, we will present the current disc design, our latest R&D progress, and the roadmap toward final integration.

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Overview of Joining Methods and Process Management in the Production of CO_2 Cooling Pipes for the TB2S detector - CMS Tracker Upgrade

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This presentation will provide an overview of the joining methods used in the production of the CO_2 cooling pipes for the TB2S detector, part of the CMS Tracker Upgrade at CERN. It will focus on both brazing and soldering techniques applied to assemble the components, as well as the cleaning methods and manufacturing processes employed. The aim is to share key lessons learned during production, with particular emphasis on the importance of independent checks and full process traceability. These aspects proved essential in a distributed production model where technical work was outsourced to multiple suppliers and service providers. The presentation is intended to inform and support future projects facing similar challenges in quality assurance and coordination across multiple partners.

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Welcome

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Capillaries production and R&D for ATLAS ITk and CMS

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The presentation will focus on the current state of the capillary R&D for the ATLAS ITk and CMS and the challenges we observed with titanium and stainless steel capillaries. Capillaries are an essential component of a cooling loop ensuring the correct flow distribution in each of the parallel branches. To achieve this goal it is desirable that a given flow through the capillary results in a well-defined pressure drop. To correctly size the capillaries for the evaporative CO_2 cooling of the ATLAS ITk and CMS we have designed and built a CO_2 blow-off rig to measure the pressure drops for production capillaries.
In the first part of this talk we will report on first measurements of production titanium capillaries, which revealed inconsistent results, both between capillaries of nominally similar dimensions and for given capillaries for repeated measurements. We think that these variations can be attributed to contamination of the inner surface of the capillaries with substances used during manufacturing processes. Contamination particles flushed out of the pipe have been analysed to establish the source of the pollution. Finally, we will report on the status of different cleaning attempts.
The focus of the second part of the presentation will be on the current state of CMS capillary production and the research of capillary connection methods in the detector. The investigated solution consists of vacuum brazed capillaries to VCR connection components. The process of vacuum brazing requires special attention and it may have an impact on the design of capillaries connectors themselves.

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Carbon Foam Air-Cooling for ALICE ITS3: Recent Progress and possible air cooling solutions for the ALICE LS3 and LS4 upgrades

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In the research and development for ALICE's LS3 upgrade, particular emphasis is placed on designing an innovative mechanical and cooling solution for the next generation of low-mass vertex detector. Assuming the use of next-generation monolithic active pixel sensors (MAPS) based on stitched technology, capable of covering large, bent-to-shape surfaces, the focus is on providing the lightest possible substrate with integrated cooling.
Within this development, shared with the CERN EP R&D program, the ALICE ITS3 relies on gas cooling methods trying to achieve a record minimum material budget (<0.09%X_0 per layer). The mechanical support employs carbon foam structures, which also serve as radiators to enhance heat exchange on the sensor area where significant power is dissipated (approximately 1 W/cm²). By the end of 2025, the project will include the production of new qualification models integrating real wafer-scale curved sensors. The successful qualification of these prototypes will enable the production of the final models to be installed in ALICE during LS3.
Carbon foam is also showing strong potential for broader applications in future detectors, including next-generation FCC-ee vertex.
In this context, the EP R&D program is evaluating how air-cooling strategies can be extended to the outer tracker layers, which cover larger areas. These solutions must be compatible with a modular detector design to facilitate the independent manufacturing and qualification of individual sensor modules, including their mechanical and thermal qualification aspects.

This talk presents the progress made in the development of ITS3, highlights key milestones, and explores potential future air-cooling approaches for larger tracking systems.

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Introduction to the DRD8 part of the meeting

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Introduction with confirmation of Milestones e Deliverables, and discussion on Institute commitments

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Experience at SuperKEKB with Interaction Region Integration

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Composite beam pipes with focus on secondary vacuum and cooling envelope for FCC-ee

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Design and system test of a cooling system for the FCC-ee vertex detector

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Robotics status and perspectives

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Introduction WP2 Goals, Milestones and Deliverables

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Updates on milestones, goals and deliverables.

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Biomimetic, hierarchical composites for novel structures

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Introduction WP3

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Exploring the heat transfer potential of supercritical CO_2

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Experimental assessment of a cascade refrigeration system CO_2-Krypton for ultra-low temperature detector cooling

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Development of embedded microchannels at CNM towards full compatibility with CMOS sensors

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Introduction WP4

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Introduction to the DRD8 part of the meeting

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Mock up status and perspectives at Frascati

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Status of CMS phase2 TBPX detector mechanics: Layer 3 prototype and final External Cylinder construction and testing, thermal tests on the mechanical structure

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During CMS Phase 2, the Inner Tracker will be upgraded. The Barrel Pixel part (TBPX), the closest to the Interaction Point, consists of 4 layers of sensors at different radii with respect to the beam pipe. Each mechanic layer is connected to the outer one through a carbon peek flange on one side and through carbon peek rings on the other side. The whole structure is supported by the External Cylinder, a carbon fiber sandwich semi-cylinder. To allow its insertion in the final position, the TBPX region, has been divided into 4 quarters, each one connected to the Tracker Forward Pixel. All TFPX and TBPX quarters will be pushed towards their final position ensuring the overlap of the sensors for all the TBPX layers.
In order to minimize the material budget, the structure is realized with radiation hard low density material, such as carbon fiber, carbon foam and carbon peek.
This talk presents the construction and the metrology campaign run on the Layer 3 prototype, the further solutions and test done to reach the desired precision.
Furthermore, the construction and metrology of the TBPX External cylinder, fundamental part for the entire project as layer support and reference, will be shown. Precision and rigidity requirements for this part guided us in the choice of material and layout.
This talk will also describe the thermal tests performed in INFN-Turin on the mechanical structure, compared with the values obtained by simulations. These tests focused into studying each thermal interface step by step, in order to understand the contribution of each thermal layer.

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Updates on Project 2.1 Design specification for future tracking detectors mechanics

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Details on the specifications and goals for the light weight mechanics structure and detector thermal management for Project 2.1

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Updates on Project 2.2 - Database development efforts

Updates on database development efforts

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Differential CTE Melt Out Tooling

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Work with Differential CTE Melt Out Tooling and Advanced Industry Tooling Techniques (Brick Kiln Composites)

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Updates on Project 2.2 - Material Characterization

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Updates on the material characterization set ups and round robin tests.

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Invited Speaker: Composites

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Importance of an adequate control system for the operation and commissioning of complex cooling systems

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By the end of 2024, the EP-DT group at CERN had developed around 30x PLC- and SCADA based control systems for various scale detector cooling applications, most of them dedicated to "on-detector" CO2 cooling systems based on the 2PACL pumped loop concept, allowing for oil-free, stable, low-temperature precise control over long distances. Over the years, both the control system size and their complexity have grown and today have reached an unprecedented scale to serve the new Trackers, Calorimeters and Timing Detectors of ATLAS and CMS under the scope of the High-Luminosity Programme of the Large Hadron Collider at CERN.
We will describe the deployed, homogenised hardware and software solutions that will allow for an efficient and unified operation across and beyond the organisation. In this presentation we will discuss implemented procedures and guidelines allowing for safe system commissioning and performance testing. We will present control system overview as well, applied PLC architectures for different detector needs.
Given the complexity of the thermofluid and control system aspects of these cooling systems, a large number of personnel will need to be well-trained in operating and troubleshooting these systems. To this end, the presentation will also discuss the development of a virtual commissioning prototype of the 2PACL cooling systems. In a virtual commissioning setup, the user operates the same SCADA as they would on a real system, and the SCADA communicates with a similar PLC, but the PLC does not regulate real hardware, it regulates a simulation of the real system. BE-ICS and TE-CRG use such setups in their groups for all sorts of pursuits: trying out control methods, 'what-if' analyses, failure scenario simulations etc. Most of all, they use these to train operators, with up to 60 hours of training material prepared in the case of Cryo. We document our own efforts at building something similar.

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Development of hydraulic interconnection and cooling supports with 3D technologies

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Mixed Reality 3D Integration Studies for CERN Accelerators

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3D automatic representation based on the planning progress

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