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First results from test runs with compact commercial CO2 cooling unit

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Two phase CO2 cooling is used in several HEP experiments. One application is for cooling the vertex detector of Belle II, using a 3 kW chiller unit (IBBelle).
Recently commercial CO2 chiller with this cooling power became available, aimed to be used in supermarkets. These units are compact and available for a fraction of the costs (purchase and service) for in-house assembled units like IBBelle.
Operating a single circuit these units are directly connected to load without intermediate CO2 circuit.
We purchased such a unit, customized it, operated and tested it in an environment similar to the Belle II VXD.
Results of these first tests will be reported and possibilities and limitations of such commercial chillers will be discussed.

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Coupled ring cooling loop design and prototyping for the ATLAS Pixel Inner System

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We present the design and prototyping of the coupled ring cooling loop to be used in the 2 phase C02 cooling of the ATLAS Pixel Inner System for ATLAS at the HL-LHC. The ring is fabricated using thin-wall titanium tubing and must be fabricated to exacting tolerances to fit the composite structure on which the pixel sensors and readout chips are mounted. The tooling developed to realize this geometry and the issues encountered during the prototype fabrication are discussed. Welded tube-tube connections are required as part of the design, such as to connect tubes to electrical breaks or to manifolds. We present bench tests of such connections using a commercial orbital welding system.

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Mechanics and Construction of the LHCb Upstream Tracker Detector

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The LHCb Detector will undergo an upgrade during the current LHC shutdown. The Upgrade Tracker (UT) is a silicon strip tracking detector being constructed as part of this upgrade. The UT will provide a fast momentum measurement for the trigger as well as function as part of the overall tracking system where it will severely reduce the presence of "ghost" tracks.

The UT Tracker consists of ~1000 ~10x10 cm^2 silicon strip sensors, with custom ASIC readout chips (SALT) arranged as modules containing flex hybrid circuits and ceramic substrates. These modules are to be mounted on staves, which are lightweight CFRP and foam sandwich structure supports having integrated CO_2 cooling. The cooling tube follows a snake-shaped routing which allows the tube to run under all ASICs and provide efficient cooling.

The design details of the UT Tracker staves and modules will be presented, as well as construction procedures and plans. Construction is now underway and is proceeding in four phases. Bare stave construction has been completed. Attachment of data flex cables, module construction and module mounting are ongoing. Precision mechanics is used for all phases of construction, through means of custom fixturing and optical QA feedback. Techniques and useful metrics for the construction processes will be presented. These include machining methods, tube bending procedure, fixture design, assembly techniques, handling of critical surfaces, role of reference datum, tolerance geometry, epoxy application, repair strategies, etc. Issues that arose during construction and solutions implemented will be detailed.

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Loading and integration of the strips end-cap tracker for the phase-II upgrade of the ATLAS detector

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The High-Luminosity LHC (HL-LHC) plans to increase the integrated luminosity of the current accelerator more than an order of magnitude, up to around 4000 fb-1, and the instantaneous luminosity from 2x1034 to ~7.5x1034 cm2s-1. The current detectors need to cope with this increased particle environment with more channels per unit area, faster electronics, and higher radiation tolerance, keeping power consumption, material, and cost to a minimum. The inner detector of the ATLAS spectrometer will be replaced by a new, all-silicon tracker, the so-called Inner Tracker (ITk). It is composed of a pixel tracker, covering the innermost layers, and a strips tracker on the outer layers. The ITk strips tracker consists of the "barrel", 4 concentric cylinders of silicon microstrips modules in the central region, and two "end-caps" in the forward regions, each containing six double-sided disks of silicon modules. The modules of the end-cap are mounted on double-sided, wedge-shaped local support structures, called "petals", with embedded cooling and data lines. Each disk contains 32 petals, each of them with 18 silicon modules. A total of 192 petals are needed for a single end-cap structure.
This contribution describes the process of loading an end-cap naked structure with fully populated petals. High precision tooling is required for this step, given the high value of the petals once fully populated (around 50-100 kEur each) and the tight position and stability requirements for the microstrips modules of the detector. The latest design of the petal insertion tool envisions a mechanical "arm" that clamps into the petal support structure and enables the safe and precise translation, rotation and tilting of the petals during insertion around the end-cap structure. Once each petal is located in its final position, additional tooling has been designed to safely lock it in place. A number of prototype versions for this tool have been designed and built at DESY in the past year. Numerous tests have been performed with this tool using dummy petals and mockup versions of the end-cap structure, both at DESY and Nikhef laboratories during the recent months, and more are scheduled in the near future. The outcome of these insertion tests will also be presented in this contribution.

The whole petal insertion process is performed with the end-cap in a vertical orientation, that is, with the beam direction pointing upwards. An end-cap frame allowing the required rotation is currently under design. This contribution will also cover the status of this multi-purpose frame. The frame hosts the petal insertion tool during the end-cap assembly, and allows access to all possible petal locations with a system of rails around it. This frame will also be used for the transport of the fully loaded end-cap, in horizontal orientation, from the institutes in which its integration takes place (DESY and Nikhef) all the way to CERN. In addition, the same frame takes care of the final insertion of the end-cap into the ITk outer cylinder, along with the rest of the ITk detector, in the SR1 surface laboratory at CERN. This is the last step before the ITk tracker, as a single unit, is lowered into the ATLAS cavern.

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CO2 cooling for the LHCb Upgrade

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A large upgrade of the LHCb detector is ongoing during the LHC Second Long Shutdown (LS2) and the Upstream Tracker (UT) will replace the TT detector inside LHCb. Being composed of new, high-granularity silicon micro-strip planes (staves) with a larger coverage, the UT will cope with an instanteneous luminosity of 2x10^33 cm^2/s adding up to at least 50 fb-1. It will provide a fast momentum measurement while also improving the overall quality of reconstructed tracks. The silicon sensors and the ASICs of the UT will be cooled using two-phase CO2. The corresponding CO2 cooling plant MAUVE is a set of two sub-plants which are dedicated to cool the VELO and the UT. In case of a sub-plant failure, the remaining sub-plant can provide backup cooling to both subdetectors.

The thermal properties of the UT box as well as the coolant flow characteristics inside the staves play an important role for the detector operation. A set of tests has been performed to determine the most suitable CO2 coolant temperature for the UT and choose an appropriate restriction orifice to create the desired pressure drop. The results of these tests will be presented in this talk. Furthremore, an overview will be given over the status of the MAUVE project including the technical design, the construction of the plant and the most recent commissioning results.

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

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The High Luminosity LHC will reach an instantaneous luminosity of $5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 140 to 200 pp collisions per bunch crossing and collect a total of 3 ab^{-1} of 14 TeV data. To cope with these challenging data conditions, the CMS Inner Tracker will be rebuilt for Phase II Upgrades. To limit particle occupancy to the per mille level and improve track resolution, we will increase the granularity of the sensors. This will result in power dissipation of approximately 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 structural components will also serve to extract heat. We present thermal transport property measurements of these structural materials using novel, custom-made apparatuses. These measurements inform finite element analysis simulations that point to potential heat transfer bottlenecks that can lead to thermal run-away in the sensors and their readout chips. To improve one of the bottlenecks, we investigate the variation of thermal conductivity of an adhesive by loading it with various compounds at varying concentrations. We also present measurements of thermal conductivity of these structural materials after irradiation.

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Fibre Optic Sensors for environmental measurements: status of the R&D at CERN EP-DT

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Due to their peculiar properties, Fibre Optic Sensors (FOS) are progressively gaining interest in all applications involving harsh environmental conditions, and/or long networks of sensing points, and/or tight space constraints for cables. All of the above conditions are met in HEP detectors.
However, as of today the use of FOS sensors in industrial or commercial application is basically limited to the measure of strain, temperature and chemical species concentration. Since 2011, the CERN EP-DT group and the Optoelectronic Division of the Department of Engineering at the University of Sannio have started the development of a new class of FOS sensors finalized to Relative Humidity (RH) sensing. The couple formed by a RH sensor combined with a temperature sensor produce a thermo-hygrometer, i.e. a miniaturized instrument capable of providing direct measurements of the local dew point (hence of the absolute humidity).
Following the first operational installation in the CMS experiment of an array of 72 FOS thermo-hygrometers based on the Fibre Bragg Grating (FBG) technology (Dec 2013 & Jan 2015), the combined team of CERN and University of Sannio started developing a second generation of FOS for relative humidity measurement, based on the Long Period Grating (LPG) technology. The technology underlying this second generation of RH-FOS sensors has been presented in the 2017 Forum, together with a discussion of the complementary performances of the FBG- and LPG-based sensors.
In March 2019, 12 LPG-based FOS have been installed for the first time in the ATLAS experiment. These sensors have been produced on different types of fibres and with different technologies, and this installation will be used as a test bench for all future applications of this second generation of FOS environmental sensors.
Meanwhile, two new lines of development have been recently launched:
1) The study, in collaboration with EPFL, of a third generation of FOS thermos-hygrometer based on the so called "distributed sensing" concept, i.e. the sensors are not concentrated on singular points along the fibre, where the gratings are produced, but the whole fibre is a continuous sensor throughout its length (up to few km);
2) The additional use of LPG sensors of the second generation as full-scale dosimeters, for continuous on-line measurement of doses from 0 to several MGy.
The talk will review the status of the R&D on FOS sensors in the CERN EP-DT group, will discuss

the first measurements provided from the first operational installation of LPG thermo-hygrometers in ATLAS, and will present the first promising results provided by the two new R&D lines.

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Design, Simulation, Manufacturing, and Validation of Prototype CMS Phase II Inner Tracker Service Cylinder

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The primary support structure for CMS Phase II Inner Tracker detectors, known as the service cylinder, has been through its first iteration of prototyping at Purdue University's Composites Manufacturing and Simulation Center (CMSC) and Purdue Silicon Detector Lab (PSDL). The mass, stiffness, and dimensional tolerance were the primary design objectives. In order to meet the extreme mechanical performance and dimensional stability requirements, a stiff yet lightweight carbon fiber composite structure has been designed via performance and manufacturing simulations, manufactured as a prototype, and validated. Several layups and configurations of structural stiffeners were investigated to minimize the deflection of the service cylinder within the permissible design envelope. Design iterations and simulation results demonstrate the diminishing returns of increased mass vs structural rigidity under the defined load cases that include the weight of the detectors and services. The importance of performing tool shape compensation to account for anisotropic material coefficients of thermal expansion and their effect on part geometry during and after manufacturing is explored and implemented. Validation exercises with digital image correlation (DIC) fiducial marker tracking emphasize the importance of designing simple, yet meaningful, test load cases that allow validation of FEA methodology. Good agreement was found between the simulation and the experiment, however further validation efforts are ongoing. With FEA methodology and boundary conditions validated for simplified load cases, more accurate load case simulations may be trusted for continuing design work until an assembled prototype allows for "full-scale" validation. Lessons learned during design, simulation, manufacturing, and validation are presented with a set of next steps to improve upon each for the creation of a successful service cylinder that meets final application requirements.

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Thermal studies for the CMS Phase II Tracker Forward Pixel detector

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Thermal finite element analyses (FEA) of representative and realistic structures in the CMS Phase II Tracker Forward Pixel detector are presented. The high granularity of the sensors and associated readout electronics (modules) necessary to take data at the High Luminosity LHC will generate 60 kW of heat that needs to be extracted for the sensors to be maintained around -20C. The FEA of representative structures for the module mounts serve to identify thermal bottlenecks in transporting heat from the modules to the mixed phase carbon dioxide cooling pipes. Using the representative structure, we explore various candidate geometries and materials to optimize the heat transfer. The FEA of realistic structures are used to estimate the temperature profile within the detector for optimal running and failure modes of the readout chips to anticipate, and thus avoid, thermal runaways in the real detector.

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Composite Structures for Tracker Detectors: a Comparison of Sandwich and Stiffened Laminate Configurations

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Support structures for tracker detectors are used to hold the detector's sensors and the associated services. During the structural design process, one of the objectives is to minimize the displacement of the sensors during operation. Two different designs are commonly used: a sandwich arrangement of two laminates and a core, and a single laminate reinforced by local eccentric stiffeners. The former design allows generally for an overall higher stiffness across the whole detector, while the latter can provide only a local increase. On the other hand, the sandwich design can entail an increase of the structural weight. As a function of the geometry and of the applied loads amplitude and distribution one design can be more effective than the other. The analytical study presented here attempts to define optimal applicability boundaries of the two design strategies.

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Mechanical Performance of Bolted Connections of Composite Structures for Tracker Detectors

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Tracker detector structures are designed to minimize the sensor displacements during operation. The various structural components are often interconnected by means of glued or bolted joints. The bolted joints can leave room for small localized displacements, decreasing the total stiffness of the structure. It is important to take into account these effects in order to properly design the structure and estimate its real behavior with accurate numerical models. To evaluate the impact of different bolted connections, a simple representative structure was built at LBNL. Weights were applied in multiple configurations, and the resulting displacements were measured by means of dial gauges. The results were then used to calibrate the numerical models, in which two modeling strategies were used to introduce the local joint compliance: contacts and MPC joints. The advantages and disadvantages of each methodology are discussed here, along with the measurements of the joint compliance. The presented results may be used in the future as a reference for joint modeling in composite structures.

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An Advanced Radiation Dose Estimation Tool for the Decommissioning of High Energy Physics Experiments

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As CERN prepares for the High Luminosity LHC upgrade (HL-LHC), several detectors & components of the experiments need to be replaced with upgraded versions designed to take full advantage of the increased luminosity.

We will present ongoing work for the creation of an integrated system for radiation intervention planning, to be used in the preparation for the decommissioning of the ATLAS Inner Detector (ID) in 2024 (LS3), which will be replaced by the new ATLAS Inner Tracker (ITk). We will discuss how the same software environment can be applied for various other radiation critical interventions, where detailed CAD drawings and dose maps are readily available.

Having been exposed to intense high energy beams for several years, creating a challenging radiation environment for personnel, the ATLAS ID will require significant manpower over several months for a complete removal of the detector and its associated services. Careful estimation and further optimization of the individual / collective dose for the personnel involved is therefore an essential part of the decommissioning planning. By combining existing CAD models of the detector with dose maps from an improved radiation simulation (FLUKA), we created a 3D virtual environment which monitors the instantaneous dose rate with respect to position within the environment. Various actions will be created in sequence, with intervention times attributed to each of them. As activated components are removed from the detector, the dose map is revised accordingly. The system then calculates the expected integrated dose for personnel following the intervention work process. Once a baseline integrated dose has been established, individual decommissioning steps can be analysed, and dose critical operations can be optimised.

Using a commercially available motion tracking system, we plan to capture the real-time position of multiple persons while training on a full-size mock-up. This will allow us to record a realistic 3D motion-path that can be imported back into the virtual environment. Importantly, stored positional data of each person during the deinstallation training can be used to directly test the potential efficiency of various shielding concepts before production, by applying a corresponding, modified radiation dose map to the existing virtual model and recalculation of the received radiation dose.s

Ultimately the system can be used for the evaluation of ongoing interventions on a daily basis. Existing CERN operational dosimeters (DMCs), that are worn by personnel during interventions exposed to radiation, record the collected radiation dose throughout the day in several second intervals. With comparison of the actual collected dose during the day against the calculated dose based on the recorded positioning data, any miss-match between radiation simulation and the real intervention can be identified and corrective measures can be taken.

As radiation levels will sharply increase with HL-LHC luminosity (LS4 and beyond), the radiation protection aspects during interventions will become significantly more challenging and will need to influence the detector design even further. With the presented simulation tool, possible placement of shielding can be simulated, and the effect of each shielding element evaluated. Necessary mounting points could be included during the design to allow swift placement and efficient protection of personal intervening.

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The large-scale CO2 cooling systems for ATLAS and CMS upgrades: design and operational aspects

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The ATLAS and CMS Phase II upgrade program foresees several detectors to be cooled with liquid 2-phase CO2 in a pumped cycle. The total cooling power in each experiment (about 300 kW in ATLAS and 550 kW in CMS) and the number of different detectors choosing the same technology (up to 4 subdetectors in CMS), calls for the CO2 cooling system to be designed, constructed and operated with a modular and standardized approach.

This talk highlights the concept of the modular design from the point of view of the component selection and qualification, the plant layout and the detector distribution. As well, the operational aspects related to the parallel operation of several plants, the redundancy schemes and their impact on the detector operation are explained.

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System Integration Issues with the Silicon Tracker of the CBM Experiment at FAIR

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The Compressed Baryonic Matter (CBM) experiment at FAIR is a heavy-ion physics experiment, conceived for high-rate beam-target interactions to allow for the exploration of the phase diagram of strongly interacting matter at highest net baryonic matter densities. The FAIR facility is currently under construction. The CBM detectors are close to desigh finish and the start of series assembly. Beam delivery to the CBM experiment is foreseen from 2024 on.
The Silicon Tracking System (STS) is the central CBM detector for charged-particle identification and momentum measurement. As a consequence of the CBM physics program, its key performance requirements are (a) resolving charged-particle multiplicities of up to 1000 in heavy-ion collisions at up to 11 GeV/nucleon projectile energy, (b) pile-up free track measurement at collision rates between 0.1 and 10 MHz, (c) momentum resolution in a 1 Tm dipole magnetic field of better than 2%, and (d) capabilities for the identification of particle decays, e.g. with strangeness content. A low-mass detector is of particular importance as the particle momenta are low when compared with those at LHC. At the same time a large aperture and standalone track reconstruction capability keeping up with the high interaction rates must be achieved. The STS design chosen comprises 8 tracking stations equipped with a total of about 900 double-sided silicon micro strip sensors. The detector's functional building blocks are low-mass modules consisting of a sensor spaced by ultra-thin read-out cables from its read-out electronics that is placed outside of the physics aperture. A total of close to two million channels will be read out with self-triggering electronics, streaming time-stamped data to a computing farm where on-line event formation and analysis is performed.
At the Forum we will address a number of issues that we have with the system integration of the STS, along with approaches made. Module assembly has been achieved using tape-automated bonding of micro cables to double-sided sensors and read-out ASICs. Two cable materials and related interconnect techniques are being explored. About 20 module variants, i.e. combinations of sensor strip and microcable lengths, are required due to the forward geometry of the experiment. Signal-to-noise is an issue in particular with the longest modules. First full modules with longest cables have been assembled and mounted onto carbon fiber support ladders. Optical survey has been developed for sensor quality assurance and ladder metrology. Some of the ladders have been installed and operated in the miniSTS detector of the miniCBM experiment at GSI-SIS18, allowing to test mechanical and functional aspects of the full detector. The thermal management of read-out and powering electronics has to be capable of removing dissipation of about 40 kW through a liquid cooling system.

The silicon sensors have to withstand an integrated particle fluence of 10^{14} n/cm^2 (1 MeV equivalent) and will be cooled to below -5 deg. C with a flow of nitrogen gas to suppress leakage currents. Electronics and sensor cooling are addressed with a separate "thermal" demonstrator, currently under construction, focusing on thermal interfaces, wall insulations and feed-throughs for the various services, as well as proving the liquid and gas cooling approach.

Discussion on future R&D and a possible R&D collaboration / **27**

Interlocking Super Modules for Future Large Area Tracking Systems

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Recent developments in the mechanical supports for the next generation of large area tracking systems at HL-LHC have established the benefits of large-scale multi-module systems. In this presentation, we report on an evolution of this approach targeted towards future large area tracking systems for future e+e- and pp collider experiments.

We will describe the design of a large-scale interlocking structure which incorporates a 4m long mechanical support, manufactured from carbon-fibre reinforced polymer, with the electrical services and cooling systems required for approximately 300 silicon strip sensor modules. This design accomplishes a high stiffness-to-mass ratio through a high moment of inertia. We will report on the development of a suitable manufacturing process which has resulted in a series of one metre length prototypes with integrated forced-air cooling channels and describe the results of an initial measurements of cooling performance.

Finally, we will describe our first attempt to integrate services like low-mass kapton cooling tubes into the structure to study the thermal performance with mono- and bi-phase cooling systems for higher power applications.

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ATLAS Pixel Endcap Structure

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The ATLAS Endcap Outer Pixel mechanical structure for the High Luminosity LHC is coming to its final stages of design. In this presentation I will report on past and current R&D of the global and local supports.

I will describe the design of the local support structure mechanics, the production techniques developed. The results from thermal and mechanical FEA will be compared with data taken on full-scale final prototypes. The global mechanics comprises three concentric cylinders which are split at the top and bottom centreline. I will describe two alternative methods of half-cylinder manufacture, discuss their relative merits and consider which is the most appropriate for this application.

In addition I will present experimental results of the metrology of prototype thin walled half-cylinders manufactured from pre-pregs with M55J fibre and LTM110 and EX-1515 resins. The geometric data will compared with the tooling and the CAD model. Data on the vibrational response of the half-cylinder prototypes will be compared to simple models using classical laminate theory and FEA. Finally, I will present a summary of other work being done within the collaboration in order to produce a fully working endcap.

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Electrical defects in co-cured bus tapes and quality control strategies

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Bus tapes are flexible solutions for powering and extracting data from compact detectors such as silicon trackers. A common strategy for assembling the bus tape is to co-cure it over carbon fiber facings that serve as tracker modules' support. The process of co-curing can introduce defects in the bus tape due to different thermal expansion between the tape material and the carbon fiber. These defects can prevent the proper operation of modules and, due to the integration of the bus tape in the CFRP core structure, would necessitate a complete replacement of a fully loaded tracker support. As such, it is important to understand these failure modes and to develop strategies to identify them in early stages of the tracker assembly.

In this talk we will discuss the failures observed in the co-cured bus tapes that will be used in the future ATLAS ITk Strips detector as well as the strategies for quality control being pursued. The large surface area of the bus tapes that will be used in this strip detector prevents manual inspection. We describe the design of a fully automated system for visual and electrical inspections of bus tapes. The techniques developed can be used for quality control of general high-density bus tapes of detectors that use similar strategy for data extraction.

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Quality Assurance Techniques as Applied to Strips Detector Barrel Staves ATLAS Phase II Tracker Upgrade

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We propose to present quality assurance techniques used at both Iowa State University and Yale University physics departments as integral parts of the ATLAS Phase II Upgrade strips detector barrel stave core production cycle. Specifically, we will address thermal imaging and bending tests as well as novel approaches to assuring structural bond integrity in composite honeycomb structures.

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The Scintillating Fibre Tracker for the LHCb Upgrade: Experience from Production and Assembly

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During the Long Shutdown 2 of the LHC, the LHCb collaboration will replace the current Outer and Inner Tracker by a single tracking detector, based on 2.42 m long scintillating fibres with a diameter of 250 μm, readout by silicon photo-multipliers (SiPM). The fibres are arranged in mats of 6 fibre-layers with a width of 130.65 mm. Eight fibre mats will form a module and are sandwiched

between honeycomb and carbon fibre composite panels to provide stability and support over the module length of 4.85 m. The modules are supported by a 4 m wide by 6 m high C-Frame structure that provides the proper stiffness to the full package. The C-Frames are also used to support electronic boards, cooling systems and services and must fit in the existing bridge/platform structure imposing tight space constraints.
The production and assembly of the full C-Frames are currently underway with the foreseen installation date for the first six to be installed at the end of the year, and the following six in the spring of 2020. The experience in production and assembly of the various precision components of the C-Frame will be presented including the large extruded aluminium I-beams, carbon fibre support cables, and scintillating fibre modules with Nomex honeycomb and CFRP panels. Additionally, the integration of the Novec cooling circuit, chilled water, dry gas, and electrical services in the confined envelope of the tracker will be presented.

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Towards the Development of Cooling Demonstrator of the CBM Silicon Tracking System (STS)

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As the core detector of the CBM experiment, the Silicon Tracking System (STS) located in the dipole magnet provides track reconstruction & momentum determination of charged particles from beam-target interactions.

Due to the expected irradiation damage (fluence - 10^{14} neq (1MeV)/cm²), the silicon microstrip sensors will dissipate < 6 mW/cm² at -10°C. Thus it is imperative to keep the sensors at or below -10°C at all times to avoid thermal runaway and reverse annealing by forced N2 cooling. The corresponding electronics connected via microcables are placed outside detector acceptance and bi-phase CO2 cooling will be used to remove ~ 40kW power dissipated.

To experimentally verify the aforementioned concepts under realistic mechanical constraints, a thermal demonstrator comprising upto 3 half-layers of STS is under development. This contribution will describe the recent R&D on several sub-components, such as CO2 cooling plant and corresponding distribution system, optimised CO2 heat exchanger plates, dummy silicon heaters and electronics board, thermal enclosure etc.

R&D on the feasibility of NOVEC mono-phase cooling as a backup for electronics cooling and using air nozzles for sensor cooling will also be mentioned. In addition, future plans on the demonstrator integration and design will be also presented.

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Ongoing R&D activities for ATLAS and CMS phase 2 upgrade CO2 cooling systems

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The CO2 cooling systems for the phase-2 upgrade of ATLAS and CMS are an order of magnitude larger in cooling power than the CO2 cooling systems developed so-far. This enlargement of the systems brings new engineering challenges which are currently being studied in several R&D programs in the CERN EP-DT-FS cooling team. A prototype cooling unit, called DEMO, of about 100 kW is being built.
A proportional enlargement of the system would lead to very large CO2 accumulators and hence large CO2 quantities stored underground. In order to reduce the volumes, a modified control concept is under study to supply the multiple plants with a common CO2 storage on the surface. A modified control mechanism to fill and empty the system is foreseen.
The enlargement of the systems also leads to large diameter transfer lines between the cooling plants in the service caverns and the cooling loops in the detector. These transfer lines typically have 2-phase flows in both horizontal and vertical orientation. The behaviour of 2-phase CO2 flow under these novel conditions is insufficiently understood and is therefore subject to a dedicated R&D program. In the CERN cooling laboratory in B153 a set-up of 8mm ID pipes is mounted in order to understand the fundamental behaviour of 2-phase flow especially in vertical pipes. Transparent sections are present for visualization of flow patterns. Following the small-scale setup, a next R&D on a real size transfer lines up to 2" will follow using the large capacity DEMO cooling plant, while smaller scale transfer lines, with the typical size of the detector to manifold ones are being tested in real scale on the CMS experiment for vertical flow effects.
A second large R&D activity is the application of CO2 as working fluid also in the primary cooling system. When used as primary cooling fluid, CO2 is referred to as R744, the refrigeration code. A R744 primary system is able to cool the underground CO2 plants directly to the air or the primary water towers on the surface. This application makes the full detector cooling to work with natural refrigerants only, ensuring a green future for the next generation cooling systems at CERN. The primary R744 cooling R&D is done in a successful collaboration between world experts from NTNU in Norway and EP-DT and EN-CV at CERN.

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R&D for a colder future in HEP

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CO2 cooling has been the ideal cooling technology for detectors since its introduction for the LHCb-VELO cooling in the beginning of the millennium. The target operational temperatures for silicon detectors have been lowered over the years stretching the CO2 cooling technology to its limits. Detector cooling typically having small tubes need a high pressure evaporative fluid to be able to remove the detector heat in an efficient way. CO2 cooling has proven to work efficiently at high pressure close to the critical point and is reducing its favorable properties by going colder. The current targets for CO2 cooling is below -40'C. CO2 cooling performs still well compared to other cooling fluids, but is loosing efficiency fast. CO2 cooling is also hitting a real hard boundary which is the tripple point, where the liquid CO2 freezes to dry-ice at -56'C.

Some future detectors are considering colder cooling temperatures. If efficient cooling with small tubes is required a different fluid is needed with a lower critical point than CO2. R&D on the heat transfer behaviour of other fluids either sub or super critical is needed. Systems with lower critical points also need a different way of operating than the current operation of the CO2 systems. A super critical cool down is needed to cool down the detector in a gentle way. This new system approach and new fluid applications needs R&D to explore the possible cooling technology for the colder future.
Beside investigating the use of fluid (or mixture of fluids) with lower critical point, the other obvious

way to cope with requests for lower temperature of the sensors is to work on thermal management design approaches minimizing the temperature difference between the sensor and the cooling fluid. The most effective solutions in this sense come from the integration of micro-structured cold plates in the detector supports, where tremendous progresses have been recently made. However, today the most developed approach relies on the application of MEMS-derived processes to the micro-fabrication of silicon devices, which prove to be extremely effective, but very expensive and difficult to integrate.
Promising developments with high potential come from the extension of additive manufacturing techniques to ceramic materials and from the introduction of innovative processes for silicon microstructuring. These subjects certainly call for active R&D.

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Production, quality assurance and integration of staves mechanics for the new ALICE Inner Tracking System

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The Inner Tracking System detector of the ALICE Experiment at CERN laboratory will be replaced in 2020. The upgraded system will be equipped with seven layers of Monolithic Active Pixel Sensors. The Tracking layers are divided in two groups: the Inner Barrel, grouping the innermost three layers, and the Outer Barrel, consisting of the outermost four layers. Each Layer is azimuthally segmented in elements called Staves. The Stave, which extends over the whole length of the respective Layer, is the basic building block of the detector. The Stave contains all structural and functional components, thus making it the smallest operable part of the detector. An array of sensors is aligned and glued on a mechanical substrate that provides stable positioning and thermal control of the sensors with use of minimum material thickness.
The production of the Stave mechanical substrates has been based at CERN to guarantee a close control of the quality of the non-standard manufacturing process, based on ultralight carbon plies lay-up with embedded kapton pipes. A quality assurance plan has been closely followed with the implementation of inspection and structured testing throughout every phase of the manufacturing process. Production of the Inner Barrel and Outer Barrel Stave mechanics has been completed and the carbon composite parts have been delivered to the four Stave construction sites, worldwide, for the integration of sensors and services.
The Staves, fully equipped with sensors and services from the construction sites, are arriving back to CERN, where they are being integrated in Layers. Finally, a detailed integration and test procedure guaranties the Staves correct installation.
In this work all aspects related to Stave mechanics mass production and quality control will be presented, while Staves installation in layers will be detailed in term of developed procedures and progress status report.

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CERN R&D lines for the mechanics of future tracking detectors

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CERN R&D lines for the mechanics of future tracking detectors
Recent innovations in the field of silicon imaging technology for consumer applications open an extraordinary opportunities for new detector concepts, and hence offer strongly improved physics scope. ALICE has presented and expression of interest for the construction of a novel vertex detector, to be installed during LS3, consisting of truly cylindrical layers based on curved wafer-scale ultra-thin silicon sensors, featuring an unprecedented low material budget of 0.05 % X0 per layer.

In standard CMOS manufacturing, the maximum size of a chip is limited to the reticle area defined by the field of view of the photolithographic process, which is typically a few centimeters in both directions. For this reason, at present small sensors are mounted edge to-edge on top of a flexible PCB module that provides the power distribution and data bus.
However, a recent technology, called stitching, allows fabricating sensors of arbitrary dimensions, the only limit being the size of the wafer. The key new idea is to make use of the stitching technology to replace such a module with a single large sensor, where power distribution is managed internally, confining to the sensor edge the interconnections to the outside world.
The large sensor will be thinned to values of about 20 µm to 40 µm, and its surface finished with plasma polishing to release mechanical stress. The possibility to bend and operate ultra-thin sensors to a curvature radius of about 20 mm seems very promising, opening the way to the construction of a silicon-only cylindrical layer.
This opens the possibility of fabricating a pixel sensor with the dimension of an entire stave. The distribution of power and electrical signals could then be done entirely inside the silicon chip and the electrical substrate would terminate close to the chip edge, where the interconnections to the chip would be realized. Concerning the elimination of the material associated with the cooling circuit, the possibility of using a low-speed (< 2 ms 1) air flow to remove the heat produced by the ITS Inner Layers by convection, in combination with peripheral liquid cooling, is considered a viable option for sensors with a power density below 20mW/cm2.
In addition the concept of a large-area sensor extended to the construction of a large silicon pixel tracker would represent a real breakthrough. ALICE has also developed plans for LS4 for a compact, next-generation multi-purpose detector, where the vertex detector is integrated with a number of tracker layers on larger radius, all equipped with MAPS pixel sensors. For such a detector the large areas of the outer layers, the costs, the assembly and the QA will drive the mechanics design choices. A "lego" modular concept, based on a modular substrate, to serve one or a limited number of chip (stitched) sensors, will allow for single module test and replacement, while it will pose the design challenge in the module's electrical and hydraulic interconnections. Alternatively, the research of technologies that can be scaled to large areas without joints shall be investigated. Ideally a continuous structural/electrical/cooling substrate with a flexible shape, interconnecting thin MAPS shall provide a cheap fully integrated solution. Cheap and disposable substrate such as carbon fibre structures embedding polyimide pipes will be exploited. At the same time the material investigation shall be extended to carbon composites that can be processed with cheaper processes for large detector volumes, especially relevant respect to the new detector dimensions; i.e. out of autoclave curing that represent a promising faster and more cost-efficient process.

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Industry presentation: Swagelok

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Fluid systems expertise isn't developed overnight. In fact, Swagelok has been perfecting the tube fitting for over 70 years. In 1947, Fred A. Lennon developed the finest tube fitting known to the industry. Since then, Swagelok has continually evolved and improved our proprietary design to meet the changing needs of our customers. From our unique metallurgy, advanced geometric design, and our unmatched performance - Swagelok tube fittings are engineered to perform under pressure. Pressure Containment, leak-tight seals and vibration fatigue resistance are just a few areas where the Swagelok Tube Fitting excels. Please join our presentation to educate yourself on the quality of our products, services, and how they will benefit you.

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Industry presentation: TBC

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Thoughts about an R&D collaboration on Detector Mechanics

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For an effective and efficient implementation of an R&D program it is mandatory to have a sustained cooperation with partners from the HEP community. The yearly 'Forum on Tracking Detector Mechanics' is a good platform to exchange ideas and update each other about ongoing work, however, R&D is only a small part of it.

Motivated by the great success of R&D collaborations like RD50 (radiation hard silicon detectors) and RD51 (micro pattern gas detectors), the suggestion is to apply the model of an R&D collaboration also to the topic of 'Detector Mechanics'. This would allow us to carry out the research, in which many of us are interested, in a constructive and efficient way, while benefitting of an organizational structure which could be adapted from the existing R&D collaborations.

A proposal on how this could be done for 'Detector Mechanics' will be presented.

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Discussion

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Closeout

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Module Construction and Wirebonding for the LHCb Upstream Tracker / Optical SmartScope-Based QA for the Construction of the LHCb Upstream Tracker

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To be added

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Prototyping of 'tilted' Rings and design of global structures and assembly sequence for the TBPS sub-detector of CMS Tracker Upgrade

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One of the most notable features of the Phase 2 CMS Tracker upgrade is a novel geometry, used in the TBPS sub-detector (Tracker Barrel with Pixel-Strip modules), in which the silicon detector modules are tilted towards the beam interaction point. Compared to traditional barrel/endcap geometries, this tilted concept provides clear advantages in terms of mass and cost saving, but poses unprecedented challenges on the mechanical design, manufacturing and assembly. This talk will present the design and manufacturing procedures of the tilted TBPS Rings as well as the design concept of the global support structure of the TBPS, their calculated mechanical performances, planned assembly sequence and tooling designs. Results obtained with prototypes made in carbon-fibre composites will also be shown.

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CO2 cooling tests and pre-heater characterisation for the CMS Phase II Outer Tracker TB2S

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The cooling system for the CMS Tracker is currently being designed within the scope of the Phase II upgrade. In order to limit radiation damage to silicon modules, and ensure detector performance for its expected lifetime, the silicon must be kept as cold as possible. Evaporative CO2 cooling is chosen because it is possible to keep a fairly constant cold temperature throughout the detector, with the addition of heat only causing the evaporation of liquid rather than an increase in bulk fluid temperature. This allows for the use of smaller mass flows and hence small pipes in a region where the material budget is to be minimised.
To evaluate the performance of the two-phase cooling system, tests have been performed on geometry representative of the Outer Tracker TB2S ladders down to -24℃ over a range of operating conditions. The obtained results can be compared to simulations using tools like CoBra to contribute to our understanding of detector cooling performance and design.
The effect of superheating has been observed in previous detector applications with CO2 cooling (particularly in ATLAS). Superheating is when the liquid CO2 passes the saturation point without evaporation occurring, the fluid continues to heat up as its enthalpy increases, obviously counterproductive to keeping the silicon modules as cold as possible. Superheating appears to be unstable, and at a certain point (distance along the pipe, or in time) the superheated fluid boils and drops in temperature to the "normal" two-phase curve. The use of a heating device clamped to the outside of the pipe ("pre-heater") to trigger bubble nucleation upstream of the modules has been explored.
Pre-heaters seem to be effective at dispelling superheating within the test setup representing a single TB2S detector cooling loop. The main parameters affecting the power required to trigger nucleation are shown to be: pre-heater length, pipe inner and outer diameters, CO2 temperature, mass flow rate and the amount of sub-cooling of the liquid.
A semi-empirical model for the pre-heater design is also proposed: starting from a few experimental data points, the model characterises a pipe made of a specific material and production process, giving the possibility to design the pre-heater for that type of pipe while changing any boundary condition (flow, power, length). The model is based on the onset conditions of nucleate boiling: for nucleation to occur on a pipe wall, the entire liquid-vapour interface of a bubble should be at a temperature above the minimum liquid superheat requirement for the bubble itself. Since the temperature in the liquid reduces farther away from the pipe surface, the lowest temperature in the liquid is experienced in the tip of the growing bubble. A simple condition is thus derived when the liquid temperature at the tip exceeds the minimum required temperature to sustain the vapour bubble, with the liquid temperature profile derived from duct turbulent flow analysis. This gives the definitions of a minimum and a maximum radius of active cavities that allow the onset of nucleate boiling. As it is generally difficult to assess what is the microscopic structure of pipes, in order to understand if the pipe surface contains cavities that are suitable to generate nucleate bubbles, experimental data is

needed in order to obtain the cavity radii range for the surface of the pipe under investigation. The model itself seems to correctly predict the impact of changing the design of the pre-heaters, catching the expected variations of their nominal power with respect to some of the parameters involved, such as the pre-heater length, the liquid CO2 temperature and its mass flow rate. A more extensive validation campaign is needed, to analyse the model behaviour when other influential variables are changed: pipe diameter, subcooling level, and pipe roughness.

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Cooling performance of CO2 boiling flows: new measurements at LAPP and CERN

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Due to its many favourable thermo-physical properties, CO2 in boiling state has been adopted as preferred refrigerant for the future generations of silicon detectors at the LHC. The data available on CO2 boiling in channels of small hydraulic diameter (say, below 3 mm) is limited and often affected by too large uncertainties. This obliges the detector designers to long iterative phases of experimental tests, which could be sensibly reduced by the availability of reliable models. In order to cope with this unsatisfactory situation, two independent experimental activities have been conducted at LAPP and at CERN.

To prepare for the High-Luminosity phase of LHC (HL-LHC), the ATLAS Inner Detector will be replaced in 2024 by the new Inner Tracker (ITk) system, entirely cooled with two-phase CO2. In the barrel part of ITk, the heat flux values flowing from the pixel modules to the cooling fluid through the brazed local support can surpass the 100 kW/m2. As the model currently used to estimate the heat transfer coefficient (HTC) has never been validated for heat fluxes of this magnitude, it was decided at LAPP to test the predictions of the ITk detector thermal behaviour with simplified prototypes of the detector local supports. The thermal performances have been extensively measured in a dedicated test setup, under a wide range of operational conditions (coolant temperature, mass flow, vapour quality…). The HTC is then extracted from the large dataset using a nuisance parameter fit and compared to the theoretical predictions. It will be presented the thermal test setup, the FEA and HTC modelling of the ITk thermal prototypes, and the fit method used to extract from our dataset the model parameters (in situ material thermal conductivities, manufacturing variability, HTC…). The experimental HTC values extracted from the dataset are compared to the CO2 model predictions, and the discrepancies discussed. The results are shown to improve the precision of the predictions over a wider working region than the one considered by the current theoretical model. The impact of the cooling pipe material (titanium vs stainless steel) on the CO2 thermal performance is also discussed.

In the meanwhile, in the context of the AIDA-2020 project, a new test stand has been designed and built at CERN to characterize with an unprecedented level of accuracy boiling flows of CO2 in mini- and microchannels with hydraulic diameter ranging from 2 to 0.1 mm. In this presentation, initial important results from this long term campaign will be presented and discussed. In particular, we will discuss the trends of heat transfer coefficient and pressure drop in stainless steel tubular evaporators of different diameters for saturation temperatures from +15 to -25 ℃, mass fluxes from 1200 to 100 kg·m-2·s-1 and heat fluxes from 5 to 35 kW·m-2. Furthermore, to improve the understanding of the physical processes occurring in mini- and microchannels, flow visualisation have also been used to explain the measured trends. In particular, the CO2 flow patterns in a silicon- multi-microchannels cold plate have been observed with a high-speed camera capable of up to 100 000 frames per second. The flow patterns have been observed for saturation temperatures from +20 to -25 ℃ and various flow rates whilst applying a fixed heat load on the face of the cold plate. With the help of these "visual maps" of CO2 flow boiling, it is possible to relate the trends of the heat transfer coefficient at specific saturation temperatures to the flow patterns occurring within the channels, which is again very valuable for the creation of new semi-empirical models on evaporative flow of CO2 in

mini- and micro-channels. In addition, the observations made show in a very spectacular way how the fluidic and thermophysical behaviour of CO2 changes dramatically with the saturation temperature and how this may affect the resulting heat transfer coefficient and pressure drops across the evaporators.

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Tour of New Wilson Facilities

Tour of Cornell's upgrades to synchrotron facilities and experimental hutches (CHESS-U), and new experimental accelerator (CBETA)

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Prototyping, integration and assembly of the CMS Phase-2 Outer Tracker Endcap

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For the High-Luminosity LHC, CMS will install a completely new silicon tracker. The future tracker will consist of two barrel parts and two endcaps (TEDD), one on each side. One TEDD is made of five double-disks, each equipped with detector modules on all four faces to ensure a complete coverage. The backbone of the mechanical structure of the TEDDs are highly integrated half-disks, the so-called Dees.
A Dee consists of a carbon fiber sandwich with a foam core and embedded cooling pipes, and module positioning inserts. A prototype in the size of one cooling sector (1/6 of a Dee) is currently being built, implementing lessons learned from previous design iterations. This prototype will be used to further develop and qualify the manufacturing process, verify production tolerances and exercise the planned reception tests, such as metrology and thermal imaging. As the prototype includes the section of a Dee that overlaps with its matching Dee in a disk, it will be also used to verify the disk assembly concept and tooling. Full size prototypes are also planned to demonstrate the production capabilities and exercise the final integration and assembly procedure.
After the Dees are equipped with modules and tested, they are combined to form disks, double-disks and finally the TEDD. With the Dees being lightweight but large and fragile objects, they need to be supported during assembly and integration. A large semi circular arc frame is being designed to support the detector parts during all necessary integration steps, which includes transport, thermal cycling and relative positioning to a high precision. For the integration, tooling to precisely align the different disks is needed before installing the connecting skeleton. Dedicated assembly stations are being designed to allow sub mm precision alignment.
The contribution will give an introduction into the design of the TEDD and the Dees. The status of the ongoing prototyping and R&D for the half-disks and details about the planned reception tests for the production of the final Dees will be presented. The plan for an assembly sequence will be discuss. The designs and prototypes for toolings to build double-disks and the final TEDD will be presented.

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Proposal for next year's forum: Frascati

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Development of advanced micro-channel cooling solutions for silicon detectors

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Position-sensitive silicon tracking detectors at collider experiments and elsewhere require advanced solutions for mechanical support and cooling. Integrated low-mass systems must be developed that offer efficient heat removal and miminize the impact of the support and cooling systems on the material budget of the detector.
Cooling the detector through micro-channels in silicon offers an attractive solution. The close contact of the sensor and the heat sink yield unprecedented cooling performance, while the close match of the thermal expansion coefficients minimize distortions of the detector. A proof of principle for micro-channel cooling is provided by the NA62 Gigatracker, that has successfully deployed micro-channels in silicon cooling plates in a HEP experiment. The LHCb VELO upgrade is expected to push the frontier further in the near future, with bi-phase cooling in micro-channels. The growing interest in the HEP community is driving increased R&D on advanced micro-channel cooling solutions. This effort is supported in part by the AIDA2020 project. Key areas of research and development are the micro-channel manufacturing process and in-house capabilities of several institutes, the establishment of reliable models to predict the cooling performance and the development of reliable and low-mass connectors. Several groups have developed integrated solutions, where the micro-channels are embedded in the silicon sensor itself.
In this contribution, a brief overview is presented of recent advances in R&D, as well as some ideas to enhance the communication and coordination of this incipient effort.

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R&D ideas in relation to robotics

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Robots of different characteristics and designs are emerging and becoming essential for solving challenging problems in industry and harsh environments. Aiming to increase safety, robots can help perform repetitive and dangerous tasks, which humans either prefer to avoid or are unable to do because of hazards, size constraints, or the extreme environments in which they take place, such as radioactive experimental areas.
The design of present HEP detectors relies on optimizing the installation, maintenance, and repair work to minimize effective dose on personnel.
Radiation levels in a future hadron collider and radiation-cooling times will severely constrain operational and maintenance scenarios. As an example, towards the end of the FCC-hh operation, the foreseen dose rate levels are around 1 mSv/h in the entire tracker cavity after about 1 week of cooling time, and the values do not decrease significantly for 1 month or 1 year of cooling time. This radiation comes mainly from the highly activated calorimeters, so the detector opening and the placement of shielding must be automated to a large extent in order to limit the dose for personnel. All this calls for detectors design and interface adaptations accounting for shielding, remote opening-manipulation and limited (short) human access as well as for a study about the use of automated and robotic solutions for services connectivity, inspection and early intervention.
R&D program shall start from the identification of possible available suitable robotic systems, compatible with the needs of future detectors, and proceed with the definition of space and interfaces to host such systems, already in the very first phase of the a detector design.

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Breakfast

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Proposal for next year's forum: GSI

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Introductory Remarks

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Tool Shape Compensation for Composite Laminate Parts and CTE Characterization for Encapsulants

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R&D ideas at DESY

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DESY and the other Helmholtz centers and institutes participating in the Helmholtz research field Matter are currently preparing the application for the next funding period, which will start in 2021. With this document we will try to increase the visibility of detector mechanics and cooling, and put more emphasis on generic R&D in these topics. In parallel to the general funding application we are preparing a funding application for a so-called distributed detector lab (DDL) that will make technologies and competences developed at a specific centre available to the whole community. If successful, DESY will establish a dedicated lab for material testing and the processing, manufacturing and diagnostics of composite materials. This lab infrastructure will be complemented by a dedicated lab for additive manufacturing to be implemented at another participating centre as part of DDL.

At DESY we are deeply involved in the upgrades of the ATLAS and CMS trackers for the HL-LHC. Over the next years we will design and integrate one tracker end cap each for both experiments. In this respect resources for generic R&D in detector mechanics and cooling are limited and at this point only a few specific projects are identified.

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R&D ideas at LBNL

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Introduction to the R&D session

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Forum Organization

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