9th Beam Telescopes and Test Beams Workshop

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Book of Abstracts

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Facilities / **1**

New Irradiation Test Area at Fermilab

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In the Fall of 2020 Fermilab began commissioning and operations of a new Irradiation Test Area (ITA). The ITA receives 400 MeV proton beam, or H-, and is capable of delivering 2.7e15 protons per hour. This beam area has a shielding cave, motion table, remote counting house, and infrastructure to support cooling and powered tests of devices during irradiation. The facility operates under the Fermilab Test Beam program and is open to user requests when beam is available. This presentation will provide an overview of design and operations at the ITA and initial beam performance.

Infrastructure & Software tools / **2**

Test platform for automated scan of multiple sensors

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The development of large scale detectors requires high throughput testing capabilities. The ideal approach for large high energy physics collaborations is to spread the testing over different institutes. However, this requires standardized equipment that, ideally, should be operable by non-experts. We propose an affordable test platform that automatically recognizes and identifies the device to test, performs a pre-programmed test, and stores the results in a database. The present version of the platform can be equipped with a radioactive source or with a laser, depending on the test requirements. Two prototypes have been built, one at CERN and one at the University of Kansas, and they will be used for the characterization of the sensor modules for the CMS MIP Timing Detector.

Facilities / **3**

Upgrades for the CERN EP Irradiation Facilities (IRRAD, Gif++) and plans beyond the Long Shutdown 2

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The upcoming High-Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) and the R&D on future accelerators (FCC) require radiation hardness tests and qualification of tracking and calorimetry detector components as well as muon gas detectors. The reference facilities at CERN for this kind of irradiation tests are the East Area Proton Irradiation Facility (IRRAD) and the North Area Gamma Irradiation Facility (GIF++).

In the first part of this presentation, the key steps for performing an irradiation experiment (preparation, execution, dosimetry, samples logistic & results availability) will be reviewed in the light of the new IRRAD Data Manager (IDM) web application developed for this purpose. The new infrastructure, control system, hardware, and software components being upgraded and available to the IRRAD users after the Long Shutdown 2 (LS2) will also be presented. Finally, a comprehensive data model for irradiation experiments, pre-requisite for developing common software tools for the irradiation facilities community at large, and a milestone for the forthcoming R&D activities within the EU-funded AIDAinnova project will be also discussed.

In the second part a short summary of the recent improvements at the GIF++ will be presented. The facility was operational with the gamma source throughout the long shutdown 2, when the workload of the facility has even increased due to several mass-production tests. We give an overview of the current test programs, the various upgrades to the facility during the LS2, the available infrastructure and plans to enhance the muon beam intensity and availability before the next SPS proton run. Possible upgrades to the facility during LS3 or beyond will be outlined.

DAQ Systems / **4**

The AIDA Trigger/Timing Logic Unit. Current status. Future Plans.

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We describe the current status of the AIDA-2020 Trigger/Timing Logic Unit(TLU) and plans for development during the AIDAInnova project.

Facilities / **5**

Physics and Radiobiology Experimental Beam Tests at the Trento Proton Therapy Center

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The Trento Proton Therapy Center is a cyclotron based proton therapy center located in Trento (Italy) where proton beams with energies from 70 MeV up to 228 MeV are used for cancer treatment. The Center started clinical operations in 2015 and since then more than 1300 patients were treated. The facility features not only two patient rooms, both equipped with 360 degree rotating gantries, but also a unique experimental room equipped with two beam lines used exclusively for non-clinical research.
The two non-clinical beamlines are used for a variety of physics, radiobiological or biological experiments and they can provide proton beams with energies between 70-228 MeV where particle rate can be tuned from 200 Hz up to 10ˆ10 Hz.
This flexibility allows a variety of measurements and tests such as characterization of solid state silicon based (pixel, drift and microstrip) tracking systems, new crystal scintillator calorimetric tests for high energy physics and space applications, development of innovative microdosimetry instruments and also high rate proton irradiation studies.
One of the two beamlines is also equipped with a unique passive beam modulator system, called double ring, used for large area proton irradiation effect studies on biological cells, silicon sensors and electronic devices.

This contribution will describe the Trento Proton Therapy Center, the Experimental Room of the Center and the instruments used for beam quality monitoring during the experiments. An overview of the experiments performed in the experimental room will be also given.

Welcome and Closing / 6

Welcome from the IAC

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Test Beam Analysis - Tracking / 7

Reconstruction and analysis of test-beam data from ATLAS ITk pixel modules with the Corryvreckan package

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"The ATLAS ITk Pixel test-beam data have been processed so far using two software packages: EUTelescope for the reconstruction and TBmon2 for the analysis. The EUTelescope package has been discontinued and therefore the ATLAS ITk Pixel group is transitioning to a new reconstruction and analysis tool: Corryvreckan. In this presentation the first use of the Corryvreckan package on existing ATLAS ITk Pixel test-beam data is presented, including software installation and configuration as well as reconstruction of typical data. A comparison of results obtained with the Eutelescope and TBmon2 packages on one side and the Corryvrekan package on the other is presented as a validation of the new tool."

Hands-on tutorials / 8

Hands-On: Silicon Detector Monte-Carlo Simulations with Allpix Squared - Beginners

Authors: Simon Spannagel[1]; Paul Schütze[1]

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Scope of the Tutorial

The goal of this tutorial is to understand the usage of basic functionalities of the Allpix Squared simulation framework and methods to extract some of the relevant quantities for sensor studies. The participants will be provided with a task and instructions, covering the basic concepts of configuring a simulation and a detector geometry, and extracting and interpreting histograms. Some prior knowledge on the framework is helpful, but not required.

Preparation

Please make sure you have access to a working version of Allpix Squared before attending the tutorial, which could be either an online version an installation of the latest release version of Allpix Squared on your computer. In addition, we provide a Virtual Box to be set up before the tutorial containing both Allpix Squared and *Corryvreckan*.

If you want to give Allpix Squared (or *Corryvreckan*) a quick try without installing it on your system, we recommend using the Virtual Box. Please follow the description provided here to download and set up a virtual machine with all required dependencies:

https://gitlab.cern.ch/jekroege/bttb9_tutorial_corryvreckan/-/blob/master/SetupVirtualMachine.md

Please find the corresponding Virtual Box here (10 GB, please download before the tutorial):

https://cern.ch/corryvreckan/VMs/AllpixSquared_Corry_Ubuntu_Minimal.ova

Due to the download size of about 10 GB this may take a while, so please do so before the hands-on.

Detailed instructions on access to Allpix Squared can be found in the manual or on the website (https://cern.ch/allpix-squared).
Other recommended options for this tutorial are to install the Docker image prior to the tutorial or to use a CVMFS installation, if access to LXPLUS or NAF is available.

Hands-on tutorials / 9

Hands-On: Everything you would like to know about Allpix Squared - Advanced

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Scope of the Tutorial

If you are a user of Allpix Squared already, but are struggling with a certain feature or the implementation of your highly specialized simulation chain, then this is the right platform for you. In this tutorial the developers of Allpix Squared demonstrate apporaches to your issues and answer your questions.

Please submit your questions prior to the tutorial via mailto:allpix.squared@cern.ch.

Preparation

Please make sure you have access to a working version of Allpix Squared before attending the tutorial, which could be either an online version an installation of the latest release version of Allpix Squared on your computer.

Detailed instructions can be found in the manual or on the website (https://cern.ch/allpix-squared). The recommended option for this tutorial is to install the Docker image prior to the tutorial or to use a CVMFS installation, if access to LXPLUS or NAF is available.

Infrastructure & Software tools / 10

What's new on Allpix Squared?

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Since the first release of Allpix^2 in fall 2017, more than 30 developers have contributed to more than 25 stable releases. Over this time, the silicon detector simulation framework has been enriched by features ranging from physics aspects such the implementation of magnetic fields in particle and charge carrier propagation, over simulation aspects like the possibility to conduct full transient simulations of signal formation and processing, to the many improvements in the framework core, simulation examples and documentation. In addition, several developments are on their way, with the next major step close to completion being a re-implementation of the framework core and module structure for a highly efficient multi-threaded simulation.

This presentation will highlight the latest, major improvements to Allpix^2 and give an insight to current developments.

Test Beam Analysis - Tracking / 11

The ΔE-TOF detector of the FOOT experiment: characterization and first results

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The main goal of the FOOT (FragmentatiOn Of Target) experiment is the measurement of the differential cross sections of the fragments produced by the nuclear interaction of the incident light ion beam (proton, Helium, Carbon, ...) with different targets (proton, Carbon, Oxygen, ...). Depending on the beam energy, the purpose of the measurements is twofold: in the $[150 - 400]$ MeV/u range,

the data will be used to evaluate the modification of the dose-depth profile in a hadrontherapy treatment, while in the $[700 - 1000]$ MeV/u range it will be used to optimize the shielding of spaceships for long term missions in deep space.
The FOOT electronic setup is composed by several detectors devoted to the measure of kinematic quantities of the produced fragments.
In order to characterise in the best way the performance of every detector, a intense test-beam campaign has been carried out since two years together with other tests and data taking foreseen in the next future.
Among FOOT detectors, a crucial role is played by the ΔE-TOF (Time of Flight) detector, composed by two layers of plastic scintillator bars. It contributes to the particle identification by providing the velocity β of the crossing fragments and their atomic number Z.
The detector was tested using protons, Carbon and Oxygen ions both at CNAO and GSI in the $[60 - 400]$ MeV/u energy range in order to study its response in a wide range of operation.
The FOOT setup and the ΔE-TOF detector as well as the results of beam tests and of the first data taking will be presented.

Facilities / 12

Test-beam and irradiation facility at the 25 MeV proton cyclotron CYRCé at Strasbourg

Authors: Ulrich Goerlach[1]; Emery Nibigira[1]

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The IPHC (Institut Pluridisciplinaire Hubert Curien) has installed a specific beam line for tests and irradiation of detectors with the 25 MeV proton beam of the cyclotron CYRCé. Beam intensities range from 1 fA to maximal 100 nA. The Cyclotron delivers a pulsed beam with a frequency of 85 MHz, which can be divided at the source by an oscillating electrostatic field of 21.25MHz down to 42.5 MHz and will allow combined detector and electronics operation at frequencies close to the LHC. An experimental setup has been developed to carry out detector and irradiation tests. The setup consists of a thin beam scintillator for triggering, a mechanical X-Y positioner for the DUT (Detector Under Test) and two reference planes of CMS-Pixel detectors. Because the air could possibly be activated at higher beam intensities, an extraction system creates a small under-pressure of 20 Pascal in the setup.

Four CMS Pixel modules have been used to built two reference planes in front and behind the detector under test (DUT), each plane consisting of two modules mounted side by side with a small overlap of about one millimetre. The pixel modules are read out by an intermediate board identical to the CMS beam telescope CHROMIE. The purpose of this telescope is to define tracks of individual protons and to determine the impact point with a spatial resolution in the order of the granularity of the DUT, approximately 100 microns, mainly limited by multiple scattering. In this talk we will describe the detector setup, the operation of the pixel modules, the electronic read-out, the trigger and synchronization system and the Data Acquisition Chain (DAQ) and we will present first test beam results of a full scale 2S CMS tracking detector. Further we will describe the opportunities in 2021 for outside users to irradiate and/or test Silicon detectors with or without cooling using the above experimental set-up

Test Beam Analysis - Tracking / 13

Performance of FBK pixel sensors with RD53A readout chip using Test Beam data collected at DESY

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The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) will require new high-radiation tolerant silicon pixel sensors for the innermost layers of tracking detectors, capable of withstanding fluences up to 2.3E16 neq/cm2 (1MeV equivalent neutrons). In this presentation results obtained in beam test experiments with FBK planr and 3D pixel sensors interconnected with the RD53A readout chip are reported. RD53A is the first prototype in 65nm technology issued from RD53 collaboration for the future readout chip to be used in the upgraded pixel detectors. The interconnected modules have been tested on an electron beam at DESY, before and after irradiation, up to an equivalent fluence of 1E16 neq/cm2. The sensors were made in FBK foundry in Trento, Italy, and their development was done in collaboration with INFN (Istituto Nazionale di Fisica Nucleare, Italy). Analysis of collected data shows hit detection efficiencies around 99% measured after irradiation. All results are obtained in the framework of the CMS experiment R&D activities.

Beam Telescopes / 14

The silicon strip telescope at the Fermilab Test Beam Facility

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In this talk the silicon strip-based telescope installed in the Fermilab Test Beam Facility will be presented. The telescope is composed by twelve planes, six upstream and six downstream the detector under test (DUT) station. Each plane is made of 640 strips with 60 μm pitch, capacitively readout by the FSSR2 chip. The alignment algorithm, based on a Kalman filter approach will be also described briefly. The resolution on both the transverse coordinate of the DUTs is around 5 μm. Some examples of test beam measurements on silicon pixel sensors for the CMS experiment phase-2 upgrade will be showed.

Facilities / 15

Frascati Beam Test Facility: from experiment to test beam.

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In this overview, we will describe the last activities regarding the INFN-LNF beam test facility (BTF) beam implementation from the LINAC point of view and the related BTF conditioning and detection capabilities. A glance at the last experiment with 300ns pulse and an overview of the lines doubling project will end our description.

Facilities / 17

The CERN PS and SPS Test Beams

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The test beam and irradiation facilities at the CERN Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) are well established. They are highly versatile and provide hadron, electron and muon beams at a configurable momentum and intensity. Depending on the year, ion beams are available as well.
As CERN is ramping up its accelerator chain again after the Long Shutdown 2 (LS2), this contribution will give an overview of the test beam facilities, their modifications and their improvements for the year 2021 and the following years.

Test Beam Analysis - Tracking / 18

Beam test of 2S module prototypes for the Phase-2 CMS Outer Tracker

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The CMS detector will be upgraded in the Phase-2 Upgrade for the operation at the HL-LHC. Among others, the silicon tracking system will be completely replaced by a new system providing an extended acceptance, an improved granularity and the feature to include tracking information into the level-1 trigger. The new Outer Tracker will consist of 2S modules with two strip sensors and PS modules with a macro-pixel sensor and a strip sensor, specialized detector modules with onboard p_T discrimination.
The functionality of current generation prototype 2S modules has been tested at the test beam facility at DESY Hamburg. With a 4 GeV electron beam, various studies are performed like efficiency scans at different positions of the module or at varying inclination angles to mimic different p_T particles. In this talk, module related preparations for the test beam are presented and first results are shown.

Test Beam Analysis - Tracking / 19

Test-beam and simulation studies of the monolithic CMOS silicon sensor CLICTD

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The CLIC Tracker Detector (CLICTD) is a pixelated monolithic sensor targeting the requirements of the tracking detector for the Compact Linear Collider (CLIC). CLICTD is fabricated in a modified 180 nm CMOS imaging process. It features a high-resistivity epitaxial layer and a small collection diode. The front-end design is based on an innovative sub-pixel segmentation scheme which allows for the reduction of the digital circuitry while maintaining the small collection diode design. In this contribution, recent test-beam results for CLICTD assemblies with sensor thicknesses between 300 and 50 micrometers are presented. In particular, the sensor performance in dependence of the incidence angle of particle tracks is evaluated. Moreover, the test-beam results are supplemented with simulation studies using a combination of 3D TCAD and Monte-Carlo simulations with the Allpix Squared framework.

Beam Telescopes / 20

Improvement of the EUDET Telescope Timing Performance

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Stringent requirements are posed on the next generations of vertex and tracking detectors for high-energy physics experiments to reach the foreseen physics goals. Hence, a large variety of silicon sensors targeting the specific needs of each use case are developed and tested both in laboratory and test-beam measurement campaigns. An increasing number of these detectors provides hit time information with high precision. The EUDET telescopes serve as high performance reference telescopes for many years with an excellent spatial resolution. In this contribution, recent results are presented showing that the reference track time resolution of the telescope can be improved from O(10ns) to below 1ns by making full use of the information stored in the data of the AIDA TLU with an upgraded firmware version. In addition, a Timepix3 reference plane with a time resolution of 1.1ns was added to one of the telescope setups to resolve ambiguities for the track timestamp for larger occupancies. The analysis was performed using the Corryvreckan framework and an example is shown how to achieve the presented improvements.

Infrastructure & Software tools / 21

Iterative image reconstruction algorithm for computed tomography with very high energy electron beam

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We present an iterative image reconstruction for a novel tomographic technique using an electron beam with energies from several hundreds megaelectronvolt to a few gigaelectronvolt. When a high-energy electron beam passes through an object, the electrons are deflected by multiple Coulomb scattering, and the angular distribution depends on the material budget of the traversed material. The trajectory of the electrons traversing a target is reconstructed using a pixel beam telescope with

sensor planes situated in front of and behind the target. The material budget distribution of the target is reconstructed from the width of the angular distribution between the incoming and the outgoing electrons. We create the sinograms of position-resolved width-estimators making use of the track reconstruction framework 'Corryvreckan'.

Conventional analytical tomographic image reconstruction based on the radon transform produces artefacts due to statistical noise and systematical effects. We developed a simultaneous algebraic image reconstruction, which suppresses statistical noise using iterative methods, and total variation superiorization, which reduce the strength of artefacts in the reconstructed images. Based on the results of the test beam experiments performed in 2020, the reconstructed images and the performance of the iterative image reconstruction algorithms will be discussed.

Beam Telescopes / **23**

MALTA CMOS sensor telescope: new developments and recent measurements

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MALTA is a novel monolithic active pixel CMOS sensor chip designed in TowerJazz 180nm imaging technology originally conceived for the phase II upgrade of the ATLAS Inner Tracker (ITk) detector. MALTA sensor has been produced on Cz substrate in view of optimising the signal for efficiency and time resolution. A beam telescope system has been developed using up to six MALTA planes with a dedicated custom readout and trigger system. The contribution will review the architecture of the system and its multiple features with particular attention to its spatial and timing resolution. Results from application with electron beam telescope, beta decay sources and cosmic rays will be presented. Preliminary tests show that the MALTA sensor can achieve a time resolution of few ns.

Facilities / **24**

The Detector Test Beamline at ELSA

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The ELSA facility at Bonn University offers a primary electron beam for two hadron physics experiments and detector test applications. The beam is extracted from a 0.5 to 3.2 GeV storage ring with an energy deviation smaller than 0.1 percent. A dedicated detector test beamline has started operation in mid 2016 and has so far served the local high-energy physics research group in several irradiation sessions. At the hadron physics experimental sites a tagged photon beam is available. The test beam is available for transnational access through the HADRON2020 EU programme.

Electron extraction rates range from 1 Hz to 1 GHz, the beam size is adjustable from 1 to 10 mm in both transverse planes. Beam parameters such as energy, extraction rate, beam size and divergence can be easily changed during dedicated beam times. A pixel beam telescope and further instrumentation is available.

The current status and the test site's infrastructure will be presented.

Infrastructure & Software tools / 25

Performance of the track reconstruction framework Corryvreckan with regard to the usage in proton therapy

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The Inner Tracker of the ATLAS experiment requires optimal performance of its pixel sensors. To test their efficiency,a precise track reconstruction and analysis for testbeam data is necessary to ensure the precise detection of particles. In the last years, track reconstruction was mostly done with the EUTelescope software, a generic and versatile framework.
In 2017, the new track reconstruction software Corryvreckan was published with the intention to reduce external dependencies without reducing the quality and versatility of track reconstruction in complex environments. The Corryvreckan framework was inspired by the modular concept of the simulation sofware Allpix^2 making it possible to implement modules for many different applications, including the analysis to investigate sensor features.
Efforts are made in TU Dortmund to use pixel sensors and track reconstruction software for proton computed tomography.
This talk presents the comparison of track reconstructions of testbeam data with the Corryvreckan and EUTelescope frameworks as well as performance tests of Corryvreckan with simulated data. The simulated data is generated with Allpix^2 and serves to test the usability of Corryvreckan with beam properties used in proton therapy.

Experiments / 26

Status of the MUonE experiment

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The measurement of the muon g-2 presently exhibits a 3.5σ discrepancy from the Standard Model prediction. In the next years, it will be measured at Fermilab and J-PARC with even higher precision. Given this experimental effort, it is extremely important to reduce also the error on the theoretical prediction, which is dominated by the uncertainty on the hadronic contribution a_μ^{HLO}.
The MUonE experiment proposes a novel approach to determine a_μ^{HLO} by measuring the running of the electromagnetic coupling constant in the space-like region, via $\mu - e$ elastic scattering. The measurement will be performed by scattering a 150 GeV muon beam, currently available at CERN's North Area, on the atomic electrons of a low-Z target. A tracking system based on the 2S modules foreseen for the CMS High Luminosity LHC upgrade will be used to detect the outgoing particles with high precision. A Test Run on a reduced detector is planned in Fall 2021, to validate this proposal. The status of the experiment in view of the Test Run will be presented in this talk.

DAQ Systems / 27

NIM+: an FPGA-based Replacement to Legacy NIM in Test Beams +

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An FPGA-based system has been developed in collaboration with FNAL and CERN to eliminate legacy NIM units and crates currently used in test beams, cosmic test telescopes, etc. Eight PM or SiPM inputs are conditioned by a Lemo-fed daughter card to a Zedboard, driving 4 NIM- and 4 TTL-level coupled outputs. Any Boolean combination of inputs can be selected for the outputs. All is controlled by a GUI on a laptop, designed to be operated by a STEM undergraduate, with no recourse to the internal VHDL.

Test Beam Analysis - Tracking / 28

Testbeam studies of passive CMOS strip sensors

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Future particle physics experiments are motivated by the increase in luminosity and thus the need for intelligent tracking detectors providing fast track and momentum information to select events of interest. The next generation tracking detectors are mostly all silicon detectors and thus finding a cost effective solution to maximise the output is important.
A recent R&D project is using CMOS technology for silicon strip sensors, which allows large and high-resistive wafers at low cost, making them a prime candidate. Also since CMOS is commercially fabricated process it provides the advantage of easier production and faster fabrication.
In this contribution, the first test beam measurements at DESY test beam facilities of novel passive CMOS silicon strip sensors developed by the ATLAS Collaboration are presented. The sensor is processed by LFoundry, employing a 150 nm CMOS technology and has three different strips design to study. The strip sensors are designed in two different lengths, formed by stitching of individual reticles. The main focus of this test beam measurement is to study the charge collection by the sensor, sensor hit detection efficiency and examine the performance of the stitching.

Test Beam Analysis - Tracking / 29

Testbeam studies of ATLAS ITk Strip modules at DESY-II

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In order to cope with the occupancy and radiation doses expected at the High-Luminosity LHC, the ATLAS experiment will replace its Inner Detector with an all-silicon Inner Tracker (ITk), containing pixel and strip subsystems. The strip subsystem will be built from modules, consisting of one n+-in-p silicon sensor, one or two PCB hybrids containing the front-end electronics, and one powerboard with high voltage, low voltage, and monitoring electronics. The sensors in the central region of the detector will use a simple rectangular geometry, while those in the forward region will use a radial geometry with built-in stereo angle.
To validate the expected performance of the ITk strip detector, a series of testbeam campaigns has been performed over several years at the DESY-II testbeam facility. Tracking was provided by EUDET telescopes, consisting of six Mimosa26 pixel planes. An additional pixel or strip plane was used to improve the timing resolution of the telescope. Tracks are reconstructed using the General Broken Lines algorithm, resulting in a spatial resolution of several microns.
This contribution will summarize the main results of these campaigns, including tracking performance and detector efficiency after irradiation. The data have been reconstructed using both the EUTelescope and Corryvreckan frameworks, and a comparison between the two will be shown. The results are also compared to predictions from simulation done with the Allpix-squared framework. Finally, a comparison has been made of the performance of several different timing planes, with implications for future testbeam campaigns.

Beam Telescopes / 31

The Argonne FE-I4 Pixel Tracking Telescope at Fermilab

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The Argonne Pixel Tracking Telescope is installed at the Fermilab Test Beam Facility to study the performance of various pixel detectors and new DAQ systems. The tracking telescope consists of six planar n-in-p silicon sensors and read out by the FE-I4 front-end chip with a pixel size of 250×50 μm^2. The telescope performance is evaluated using a 120 GeV proton beam. The measured spatial resolution of the telescope plane is 72 µm in the X-direction and 13 µm in the Y-direction. These results are consistent with simulated results produced using the allPix2 software.

Test Beam Analysis - Tracking / 32

Test-beam performance evaluation of CLICpix2 fine-pitch hybrid silicon pixel detector prototypes

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The experimental conditions at future colliders pose new challenges for silicon pixel technologies. In particular, the next generation of inner detector sub-systems will require simultaneously high efficiency, high resolution, low material budget, and low power consumption pixel detectors. One example is the vertex detector of the proposed Compact Linear Collider (CLIC), an electron-positron collider achieving centre-of-mass energies between 380GeV and 3TeV. To fulfil these ambitious targets for the inner detectors, the CLICpix2 fine-pitch hybrid readout ASIC has been designed using

a 65 nanometre CMOS process. The ASIC has 25x25 micrometre pitch pixels and is capable of simultaneous per-pixel charge and time measurements. CLICpix2 samples have been bump-bonded to 130 micrometre planar active-edge silicon sensors and their performance assessed through detailed test-beam data analysis. This contribution will present the performance evaluation of two CLICpix2 planar sensor assemblies, focusing on spatial resolution, timing resolution, and efficiency measurements.

Analysis - Calorimetry / 33

A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system: beam test results

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The expected increase of the particle flux at the high luminosity phase of the LHC (HL-LHC) with instantaneous luminosities up to L ⊠ 7.5×10ˆ34 cm−2 s-1 will have a severe impact on the ATLAS detector performance. The pile-up is expected to increase on average to 200 interactions per bunch crossing. The reconstruction and trigger performance for electrons, photons as well as jets and transverse missing energy will be severely degraded in the end-cap and forward region, where the liquid Argon based electromagnetic calorimeter has coarser granularity and the inner tracker has poorer momentum resolution compared to the central region. A High Granularity Timing Detector (HGTD) is proposed in front of the liquid Argon end-cap calorimeters for pile-up mitigation and for bunch per bunch luminosity measurements.
This detector should cover the pseudo-rapidity range from 2.4 to about 4.0. Two silicon sensors double sided layers are foreseen to provide a precision timing information for minimum ionizing particle with a time resolution better than 50 ps per hit (i.e 30 ps per track) in order to assign the particle to the correct vertex. Each readout cell has a transverse size of 1.3×1.3 mm2 leading to a highly granular detector with about 3 millions of readout electronics channels. Low Gain Avalanche Detectors (LGAD) technology has been chosen as it provides an internal gain good enough to reach large signal over noise ratio needed for excellent time resolution.
Several test-beam campaigns have been conducted at CERN SPS H6 and at DESY T22 beamlines in the past 3 years. Proton and neutron irradiated LGAD prototypes for the HGTD were tested from different technologies and manufacturers. Single pads and 2×2 arrays with a pad size of 1×1 mm2 are compared for achieved collected charge, timing performance, post-irradiation efficiency and uniformity at fluences up to 2.5e15 neq/cm2. A time resolution of < 50 ps is observed in most cases, while integrating timing information to the EUDET system allows for a surface resolution of less than 50 μm. The triggering architecture, picosecond synchronization scheme and analysis logic will also be presented as well as application-specific electronics and components.

Experiments / 34

PADME experiment at the Beam Test Facility of Laboratori Nazionali di Frascati

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The experiment PADME is installed at the Beam Test Facility of the INFN Laboratori Nazionali di Frascati and its main goal its to search for a light boson A′ associated to a broken U(1) gauge symmetry (usually called dark photon) acting as a neutral portal between the visible and the dark sector. PADME has collected data in two runs. The first one used a secondary positron beam, but the analysis showed a high beam related background. In order to lower this background, a primary beam was used in run II. In addition, part of the beam line was also modified to have even less background and improve the sensitivity for the dark photon search. The physics processes used to evaluate the background are positron-electron annihilations in two photons and positron Bremsstrahlung.

Beam Telescopes / 35

The Very Large HV-MAPS Tracking Telescope

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The MuPix-telescope is a continuously evolving tracking telescope with very high rate capabilities that makes use of the most recent high-voltage monolithic active pixel sensor (HV-MAPS).
The nominal structure consists of three tracking layers of 100 μm thin HV-MAPS chips, at present MuPix10, and a DUT layer, complemented by scintillating tiles for additional time information. MuPix10 is a completely monolithic sensor with an active area of about 20 mm$\times$20 mm, manufactured in the 180 nm HV-CMOS process at TSI semiconductors with a pixel size is of 80 μm$\times$80 μm. The trigger-less readout uses a column-drain architecture with on-chip zero suppression. 8b/10b encoded hit data is sent out by three serial links with up to 1.6 Gbit/s each.
In the context of pixel sensor R&D, this telescope is used to investigate efficiency, time resolution, and noise behaviour of different MuPix-like sensors. In this talk, the telescope concept is introduced. Highlights of several test beam campaigns at DESY and PSI will be presented which have been performed using a MuPix10- and an ATLASPix3-telescope.

Test Beam Analysis - Tracking / 36

Production plans of the Enhanced Lateral Drift sensors

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Future experiments in particle physics need a few-micrometer position resolution in their tracker and vertex detectors. Instead of scaling down pitch sizes, the so-called enhanced lateral drift (ELAD) sensor concept seeks to improve the position resolution by increasing the lateral size of the charge distribution already during the drift in the sensor material. The ELAD sensor design has been optimised using SYNOPSYS TCAD tool. The geometry of the buried implants, their doping concentration and the position inside the sensor were optimised for different sensor thicknesses and different types of the substrate.

To estimate the position resolution of an ELAD sensor, test beam simulations using the AllPix2 software have been performed applying the realistic electric field profiles from the TCAD simulations. In the AllPix2 simulations, 2D and 3D electric fields have been used. Results of the geometry optimisation are shown realising an optimal charge sharing and hence position resolution.

A position resolution of a few micrometers is expected by using buried implants without relying on a Lorentz drift or tilted incident angle. The production plans and future ELAD sensors applications are presented.

Test Beam Analysis - Tracking / 37

A novel GAGG/CsI scintillation phoswich detection device

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New GAGG/CsI phoswich assemblies are being developed at the Galician Institute for High Energy Physics, aiming to provide improvements in sensitivity, and spatial resolution for PET and SPECT medical imaging devices. The phoswich technique is used in PET developments to improve spatial resolution by obtaining the depth of interaction (DOI) measurement. In this work, a scanner detector made of two heads of CsI and novel GAGG scintillator phoswich units, and with ADP-based readout, is presented. The first proof-of-concept with a prototype detector and simulations proved that the conceptual design described is a suitable candidate por a PET and SPECT imaging scanner. The first reconstructed images both with real and simulated data are shown. In addition, we propose also to use such device as a monitoring tool of gamma emission in test beams.

Analysis - Calorimetry / 38

Performance of CMS HGCAL silicon module prototypes in beam tests

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Contribution will be presented in two parts:
I.
In 2027 CERN is expected to start the High-Luminosity LHC (HL-LHC) phase. HL-LHC will integrate 10 times the current luminosity, leading to a high pile-up rate and unprecendent radiation levels. In order to cope with such a harsh environment and maintain the current physics performance, a major upgrade of the LHC detectors is required. As part of the HL-LHC detector upgrade programme, the CMS experiment is developing a High Granularity Calorimeter (HGCAL) to replace the existing endcap calorimeters. The HGCAL will be realised as a sampling calorimeter, including 36 layers of silicon pads and 14 layers combining both silicon and scintillator detectors interspersed with metal absorber plates. Prototype modules based on 6-inch hexagonal silicon pad sensors with pad areas of 1.0˜cm^2 have been constructed. Beam tests of different sampling configurations made from these modules have been conducted at the CERN SPS using beams of charged hadrons and positrons with momenta ranging from 20 to 300˜GeV/c. Beam tests play a key role in the validation of the detector's design as well as in the study of the expected physics performance. In October 2018 the first large scale prototype of HGCAL, consisting of O(100) modules, was tested.

After a general overview of the CMS upgrade campaign for the HL-LHC, a more detailed description of the HGCAL and the experimental set up used in the test beam, the contribution describes the assessment of the electromagnetic compartment's performance. Besides the standard quantities of calorimetry, such as energy resolution and linearity, the high granularity of the prototype is exploited to characterize longitudinal and transversal profiles, by measuring the average shower depth and the Moliere Radius. Measurements of the position and angular resolution are also presented. Data are compared with a dedicated GEANT4 Monte Carlo simulation and an excellent agreement is found for all the observables studied.

II.
The existing CMS endcap calorimeters will be replaced with a High Granularity Calorimeter (HGCAL) for operation at the High Luminosity (HL) LHC. Radiation hardness and excellent physics performance will be achieved by utilising silicon pad sensors and SiPM-on-scintillator tiles with high transverse and longitudinal segmentation. One of the major challenges of the HL-LHC will be the high pileup environment, with interaction vertices spread not only in position, but also in time. In order to efficiently reject particles originating from pileup, precision timing information of the order of 30 ps will be of great benefit. In order to meet such performance goals, the HGCAL will provide timing measurements for individual hits with signals above 12 fC (equivalent to 3-10 MIPs), such that clusters resulting from particles with pT > 5 GeV should have a timing resolution better than 30ps.

In order to assess the technical feasibility and physics performance of such a design, beam tests were performed with a prototype of HGCAL silicon modules at the CERN SPS in 2018. We present the detector and DAQ components related to the precision timing evaluation, as well as calibration techniques and preliminary results on the timing performance of the prototype.

DAQ Systems / 41

Recent Improvements of the Caribou DAQ System

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Developing a new silicon detector requires significant effort for preparing the readout hardware and software for the prototype to be operated in the laboratory and test beams. The Caribou DAQ framework significantly reduces the development effort and cost for such readout systems. By utilizing modern system-on-chip (SoC) platforms, it combines programmable logic and a processing system and thereby brings unprecedented flexibility to the DAQ design. A universal interface card connects the SoC with the detector prototype, housing power supplies for biasing as well as DACs and ADCs for setting and measuring operational parameters, test pulses, etc. Through this versatile hardware and the modular design, the turnaround time for supporting new detectors is minimized. The system is completed by a set of configurable firmware blocks for commonly used functionality as well as the DAQ software Peary.
This talk presents the Caribou system and gives an overview over recent developments, such as a new and improved hardware revision, integration of oscilloscope readout, and integration of the new ATTRACT FASTpix chip.

Analysis - Calorimetry / 42

Beam Tests of the CALICE AHCAL

Authors: Jiri Kvasnicka[1]; CALICE Collaboration[None]; Lorenz Emberger[2]; Fabian Hummer[2]; Ivan Popov[2]; Frank Simon[3]; Lorenz Konrad Emberger[4]

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The Analogue Hadron Calorimeter (AHCAL) developed by the CALICE collaboration is a scalable engineering prototype for a detector at future electron-positron energy frontier colliders. It is a sampling calorimeter of steel absorber plates and 3*3 cm^2 plastic scintillator tiles individually read out by silicon photomultipliers (SiPMs) as active material. The front-end ASICS (SPIROC2E) are integrated into the active layers of the calorimeter. They are designed for minimal power consumption by rapidly cycling the power according to the beam structure of a linear accelerator.

A large prototype with 38 active layers of 72*72 cm^2 size with nearly 22000 readout channels has been constructed, commissioned and tested in particle beams at DESY and CERN in 2018. While the analysis of these data is progressing, alternative scintillator geometries (mega-tiles instead of tiles individually wrapped in reflective foil) and an alternative readout ASIC (KLauS) have been studied in further beam tests of small prototypes. In addition, the hit time resolution has been investigated (see also separate abstract).

This presentation gives an overview of the AHCAL engineering prototype and its recent beam tests.

One of the main design drivers at future energy-frontier e+e- colliders is the precise determination of the energy of particle jets. This is achieved with detector designs optimized for the particle flow paradigm. CALICE is an R&D collaboration focussed on the development of highly granular calorimeters optimized to aid this paradigm by providing high spatial resolution. The Analogue Hadronic Calorimeter (AHCAL) is one of the detector concepts based on the SiPM-on-Tile technology, using scintillating tiles read out by Silicon Photomultipliers. A key aspect of the recently completed technological prototype is the capability for single-cell time stamping on the nanosecond level, which is important for background rejection and may provide additional benefits for energy resolution and shower separation. To investigate the intrinsic time resolution of this technology, a test beam setup has been designed and tested at DESY in October 2020. In this setup four scintillator tiles arranged as a "beam telescope"are read out by precise digitizers, allowing detailed studies of the time structure of the detector response. This contribution focusses on the details of the experimental setup as well as on the discussion of first results.

Test Beam Analysis - Tracking / 43

The MightyPix HV-CMOS sensor for LHCb Upgrade 2

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The LHCb collaboration is studying options for an Upgrade 2 of the experiment, to be installed in the long shutdown LS4 of the LHC. Studies for the three planar tracking stations downstream of the LHCb spectrometer magnet focus on a mixed detector technology, with Scintillating Fibres covering the outer part of each tracking station and a silicon pixel detector based on HV-CMOS technology covering the region of highest particle density in the center of the tracking stations. A first set of HV-CMOS prototype sensors, with pixel sizes of $50 \times 165\ \mu\text{m}^2$ and $100 \times 165\ \mu\text{m}^2$ has been tested using a MuPix10 beam telescope in a test beam at DESY in October 2020. The test beam data are analysed using Corryvreckan. A second test beam at DESY is scheduled for March 2021. We are going to present some results from the first test beam and our plans for the future, including tests of irradiated sensors.

Analysis - Calorimetry / 44

Beam Tests of the first CMS HGCAL Tilemodule prototypes

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For the HL-LHC phase, the calorimeter endcap of the CMS detector will be upgraded with a High Granularity Calorimeter (HGCAL), a sampling calorimeter which will use silicon sensors as well as scintillator tiles read out by silicon photomultipliers (SiPMs) as active material (SiPM-on-tile). The complete HGCAL will be operated at -30 degC. The SiPMs will be used in areas where the expected radiation dose during the lifetime of the detector is up to $5*10^{13}$ neq/cm^2. The design of the SiPM-on-tile part is inspired by the CALICE AHCAL.

The basic detector unit in the SiPM-on-tile part is the tilemodule, consisting of a PCB with one or two HGCROC ASICs, reading out up to 96 tiles with SiPMs. The first functional tilemodule prototypes have been constructed with HGCROC2 ASICs and SiPMs which are candidates for the HGCAL production. They have undergone beam tests at DESY and Fermilab, investigating the interplay of the components and evaluating the performance with several scintillator tile types. First test were also peformed with irradiated SiPMs.

Facilities / 45

Status Report on the DESY II Test Beam Facility and the EUDET/AIDA Beam Telescopes

Authors: Lennart Huth[1]; Adrian Herkert[1]

[1] *Deutsches Elektronen-Synchrotron (DE)*

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The DESY II Test Beam Facility provides user groups with three test beams of several kiloelectrons per second with energies between 1 and 6 GeV - typically for around 40 weeks every year.

As part of the test beam infrastructure, permanently installed EUDET-type beam telescopes are available to all users. They have been successfully operated for more than ten years and still provide a competitive spatial resolution. However, today's requirements for particle detectors, for example in terms of time resolution and readout bandwidth, generally exceed their capabilities. Plus, the last available MIMOSA26 pixel sensors are about to reach their end of life. Several developments are therefore ongoing that aim at developing successors of the current beam telescopes.

This presentation will recap the operation of the DESY II Test Beam Facility in 2020, report on plans for 2021, and summarize the developments around the EUDET/AIDA beam telescopes.

Overview Lectures / 46

Lecture: Front-end electronics and optical links

Author: Alberto Valero Biot[1]

[1] *Univ. of Valencia and CSIC (ES)*

Corresponding Author: alberto.valero@cern.ch

Data acquisition electronics for particle detectors is generally structured into front-end and back-end systems. The front-end electronics must be placed close to the sensors in order to minimize the noise. Thus, they are usually located inside the detector which typically implies a high radiation environment. It includes an analog part with a signal conditioning stage which depends on the sensor type and the magnitude of interest. Then, the signals are digitized and after an event selection transmitted through optical links to the back-end system located in the counting rooms.
The front-end electronics is usually implemented with radiation tolerant custom ASICs but depending on the radiation levels the utilization of Commercial Of-The-Shelf components is also possible.
Over the past two decades the speed of optical fiber communications has increased one order of magnitude having a great impact in the architecture of new data acquisition systems. Part of the former front-end functionalities can be moved now to the off-detector system in a radiation free environment.
In this presentation we will cover the main aspects of the data acquisition electronics systems for particle detectors and their evolution over the past 20 years.

Hands-on tutorials / 47

Hands-on: Test-beam Reconstruction with Corryvreckan

Author: Jens Kroeger[1]

[1] *Ruprecht Karls Universitaet Heidelberg (DE)*

Corresponding Author: kroeger@physi.uni-heidelberg.de

Corryvreckan is a modular test beam data reconstruction and analysis framework initially developed within the CLICdp collaboration, and used by a growing community including from many different experiments and institutes. Its modular structure allows for a separation between the framework core and the implementation of the algorithms in each module. This allows users to 'plug-in'the required modules and configure their parameters easily from one configuration file.

This 2.5h tutorial will guide you through the Corryvreckan framework and its functionality. You will learn how to configure your analysis, obtain result plots for your devices-under-test, and how to monitor you data quality online during data taking. In particular, the flexible event building mechanism will be explained and examples including the AIDA TLU and the EUDAQ2 event loader will be covered.

Preparation:

If you want to give *Corryvreckan* (or *Allpix Squared*) a quick try without installing it on your system, please follow the description provided here to download and setup a virtual machine with all required dependencies:

https://gitlab.cern.ch/jekroege/bttb9_tutorial_corryvreckan/-/blob/master/SetupVirtualMachine.md

Due to the download size of about 10 GB this may take a while, so please do so before the hands-on.

Alternatively, you can install Corryvreckan (v2.0.1 or latest) on your computer. In any case, the different installation options will be discussed in the tutorial and can be followed along.

If you decided to go for the Virtual Box, you're all set up. Otherwise continue reading.

Please clone the git repository with the example configuration file prior to the tutorial:

```
git clone https://gitlab.cern.ch/jekroege/bttb9\_tutorial\_corryvreckan
```

and download the example data sets:

```
cd bttb9\_tutorial\_corryvreckan/data

./download\_example\_data\_01.sh     (only this if the connection is slow)

./download\_example\_data\_02.sh

./download\_example\_data\_03.sh
```

More information can be found on the Corryvreckan website or on the Corryvreckan GitLab repository:

https://cern.ch/corryvreckan
https://gitlab.cern.ch/corryvreckan/corryvreckan

Overview Lectures / 48

Lecture: Silicon Processing Techniques

Co-author: Tobias Wittig [1]

[1] *CiS Erfurt*

We will give an overview of what kind of silicon processing techniques exist and how they can be applied to produce silicon radiation detectors. After an introduction into microsystem technology and its equipment, we will discuss the main steps of how to process a simple planar radiation detector. The differences to conventional, industrial CMOS processes will be pointed out in particular. We will end with special cases of radiation detectors like 3D-sensors, active edges and ELAD: which challenges are present and which technologies are needed for their realisation.

Welcome and Closing / 49

Official Welcome Address

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Welcome and Closing / 50

Welcome & Information from local organisers

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Welcome and Closing / 51

Introduction to Hands-on Sessions

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Overview Lectures / 52

Lecture: Interconnects and Assembly Technologies for Hybrid Pixel Detectors

Author: Thomas Fritzsch[1]

Co-authors: Hermann Oppermann [1]; Mario Rothermund [1]

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Hybrid pixel detector modules are the basic building blocks of vertex detectors in HEP as well as solid state detector cameras for x-ray imaging. A pixelated sensor chip, made of silicon or III/V semiconductor, is connected to one or more electronic readout chips by thousands of electrically conductive interconnect structures.

The talk will give an overview of different types of interconnection and assembly technologies and their specific potential. Solder bump bonding, transient liquid phase bonding, metal-metal direct bonding and metal-oxide hybrid bonding are assembly technologies that will be described in this talk. In addition, the required number of modules is important for the definition of an appropriate assembly technique. The described technologies cover the range from single chip bumping for prototyping up to 300mm wafer bumping for future detector upgrades.

Beside the overview of common and advanced assembly technologies some examples of more complex electronic packaging approaches will be described more in detail. This part will include the 3D packaging technology of electronic readout chips with through silicon vias (TSV). Assembly and test results of hybrid pixel detector modules using TSV readout chips will be shown.

Hands-on tutorials / 53

Hands-on: Test-beam Reconstruction with Corryvreckan

Author: Jens Kroeger[1]

[1] *Ruprecht Karls Universitaet Heidelberg (DE)*

Corresponding Author: kroeger@physi.uni-heidelberg.de

Corryvreckan is a modular test beam data reconstruction and analysis framework initially developed within the CLICdp collaboration, and used by a growing community including from many different experiments and institutes. Its modular structure allows for a separation between the framework core and the implementation of the algorithms in each module. This allows users to 'plug-in'the required modules and configure their parameters easily from one configuration file.

This 2.5h tutorial will guide you through the Corryvreckan framework and its functionality. You will learn how to configure your analysis, obtain result plots for your devices-under-test, and how to monitor you data quality online during data taking. In particular, the flexible event building

mechanism will be explained and examples including the AIDA TLU and the EUDAQ2 event loader will be covered.

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Welcome and Closing / **54**

Official Closing Words

Welcome and Closing / **55**

Closing Session

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Hands-On: Silicon Detector Monte-Carlo Simulations with Allpix Squared - Beginners

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Scope of the Tutorial

The goal of this tutorial is to understand the usage of basic functionalities of the Allpix Squared simulation framework and methods to extract some of the relevant quantities for sensor studies. The participants will be provided with a task and instructions, covering the basic concepts of configuring a simulation and a detector geometry, and extracting and interpreting histograms. Some prior knowledge on the framework is helpful, but not required.

Preparation

Please make sure you have access to a working version of Allpix Squared before attending the tutorial, which could be either an online version an installation of the latest release version of Allpix Squared on your computer. In addition, we provide a Virtual Box to be set up before the tutorial containing both Allpix Squared and *Corryvreckan*.

If you want to give Allpix Squared (or *Corryvreckan*) a quick try without installing it on your system, we recommend using the Virtual Box. Please follow the description provided here to download and set up a virtual machine with all required dependencies:

https://gitlab.cern.ch/jekroege/bttb9_tutorial_corryvreckan/-/blob/master/SetupVirtualMachine.md

Please find the corresponding Virtual Box here (10 GB, please download before the tutorial):

https://cern.ch/corryvreckan/VMs/AllpixSquared_Corry_Ubuntu_Minimal.ova

Due to the download size of about 10 GB this may take a while, so please do so before the hands-on.

Detailed instructions on access to Allpix Squared can be found in the manual or on the website (https://cern.ch/allpix-squared).
Other recommended options for this tutorial are to install the Docker image prior to the tutorial or to use a CVMFS installation, if access to LXPLUS or NAF is available.

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Hands-On: Everything you would like to know about Allpix Squared - Advanced

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Scope of the Tutorial

If you are a user of Allpix Squared already, but are struggling with a certain feature or the implementation of your highly specialized simulation chain, then this is the right platform for you. In this tutorial the developers of Allpix Squared demonstrate apporaches to your issues and answer your questions.

Please submit your questions prior to the tutorial via mailto:allpix.squared@cern.ch.

Preparation

Please make sure you have access to a working version of Allpix Squared before attending the tutorial, which could be either an online version an installation of the latest release version of Allpix Squared on your computer.

Detailed instructions can be found in the manual or on the website (https://cern.ch/allpix-squared). The recommended option for this tutorial is to install the Docker image prior to the tutorial or to use a CVMFS installation, if access to LXPLUS or NAF is available.