2.9 Detector Research & Development

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The Nikhef Detector R&D group focuses on particle tracking and radiation imaging, developing novel gaseous and semiconductor based pixel detectors. We have presented at the IEEE-NSS conference the most precise gaseous pixel detector to date for measuring the position of individual ionisation electrons. This leads to improved angular (2.5 degrees) and position (in-plane 10 μm) resolutions on fitted tracks. This finds applications in self-triggering and on-chip pattern recognition for use in for example the ATLAS L1 trigger or Proton Radiography. To further enhance the capabilities of our pixel detectors and to be ready for novel detector concepts we started evaluating the requirements for the next generation readout chips, *e.g.* the successor of the Timepix3 ASIC (application-specific integrated circuit).

Together with the Nikhef Dark Matter group we have constructed XAMS –a Xenon facility in Amsterdam– now operational to investigate different detector technologies in a dual-phase Xenon time projection chamber (TPC). Work together with the Nikhef Gravitational Physics group led to alignment and monitoring systems for Virgo's optical test masses, a program to develop ultra-sensitive accelerometers for future Gravitational Wave detectors, and experimental studies to utilise mono-crystalline sapphire cantilevers for low-frequency suspension. Various projects have applications outside our field and encourage valorisation activities: the development of scientific instrumentation towards commercial applications outside the fields of (astro)particle physics.

A Silicon telescope for detector characterisation

Within the scope of the LHCb VELO upgrade project a particle tracking telescope has been constructed based on the Timepix3 ASIC. This ASIC has been jointly developed by CERN, Nikhef and Bonn University. The telescope consists of eight sensor planes, equally divided in two arms, and with the detector under test mounted on translation and rotation stages in the centre of the telescope. Each sensor plane consists of a 300 μm thick silicon sensor bump bonded to the Timepix3, which features 55×55 μm^2 pixels, and has a total active area of 2 cm^2. The telescope is read out with the SPIDR readout system, which has been developed at Nikhef, and is (partially) funded by the AIDA FP7 project. Extensive commissioning of the telescope was performed during the summer with beams from both the PS and SPS beam lines at CERN. In the second half of 2014 the telescope has been successfully used at the 180 GeV mixed hadron beam at SPS to characterise the first prototype silicon sensors of the VELO upgrade. Thanks to the excellent pointing resolution of less than

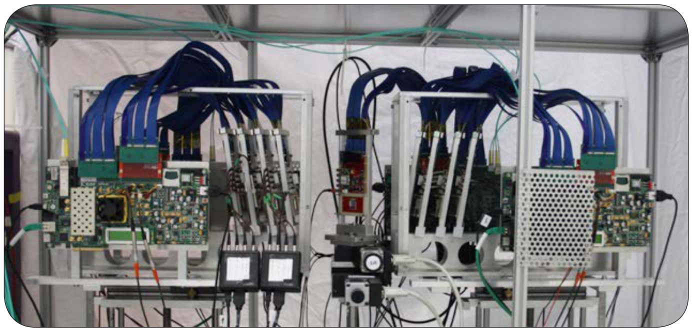

Figure 1. LHCb telescope with eight sensor planes bonded to Timepix3 front-end chips and read out by the SPIDR data acquisition system

2 μm, high resolution time tagging, and the enormous track rate capabilities (10 Mtrack/s), detailed studies of the sensors, and behaviour of the corresponding readout ASICs are now possible. Besides the VELO, also other LHCb upgrade groups and the Nikhef *GridPix* development benefitted from the availability of the telescope.

The Velopix design, which is the pixel readout chip tailored to the upgrade of the LHCb VELO, is progressing. One of the key building blocks, a 5 Gbit/s serialiser, has been submitted as a small test chip and subsequently characterised in the lab. The VeloPix project suffered from a serious delay because of a change of foundry for the 130 nm technology, which was triggered by the fact that the previous vendor could no longer guarantee the availability of the process to us for the timespan of the project.

Medical Instrumentation

In the Nikhef detector R&D group, a number of medical imaging projects are ongoing. The main focus is X-ray imaging and in particular spectral X-ray computed tomography (CT). With hybrid pixel detectors based on the Medipix3 chip it is possible to both count the number of photons, as well as separate these detected photons in a number of energy bins. This is achieved with a single detector while industry uses multiple detectors or multiple irradiations. As opposed to the mainstream use of energy information after CT reconstruction, a statistical approach is used to include energy information directly in the reconstruction algorithm. In this way, beam hardening artefacts can be removed and particular elements like contrast agents identified.

Within an ERC Proof-of-Concept grant with Utrecht University on mammography developments, the aim is to apply Medipix3 based detectors to enhance the contrast between calcifications and tumors. At the Utrecht Medical Centre a standard X-ray system is used for diagnosis of patients. The research goal is to improve this diagnostic tool, together with local radiologists, by adapting our Medipix3 system such that realistic phantoms can be measured yielding additional information for physicians.

Silicon is widely used as radiation detection medium and became a mature technology but has limited absorption capacity, especially for higher energetic X-rays used in medical applications. Research with Philips in the INFIERI training network tries to overcome limitation by edge-on illumination of Silicon sensors, which increases the effective absorption depth for X-rays. This project also develops new methods of signal processing per pixel in the read-out chip, to ensure maximum use of the dose applied to a patient.

Several proton therapy centers for advanced cancer treatment are envisioned in The Netherlands in the near future. The R&D group works with KVI-CART in Groningen on a system for proton radiography (PR): imaging with protons to develop advanced treatment plans. This allows to irradiate a patient with higher precision than currently possible with treatment plans solely based on X-ray CT data. Our proton radiography system uses Time Projection Chambers (TPC) based on our gaseous pixel detectors *Gridpix* to minimise scattering of the protons, thus providing accurate 3D proton tracks without the combinatorial background unavoidable with silicon based detectors. Over the last few years the system has evolved, such that the small density differences one finds in the human body can be distinguished. Next steps are to increase the active area of the detector and to work towards combining X-ray CT data with proton imaging data to increase the precision of the proton beam stopping power distribution. Overall this will lead to a substantial reduction of irradiation of healthy tissue and as such a reduction of negative side effects like the occurrence of secondary tumors.

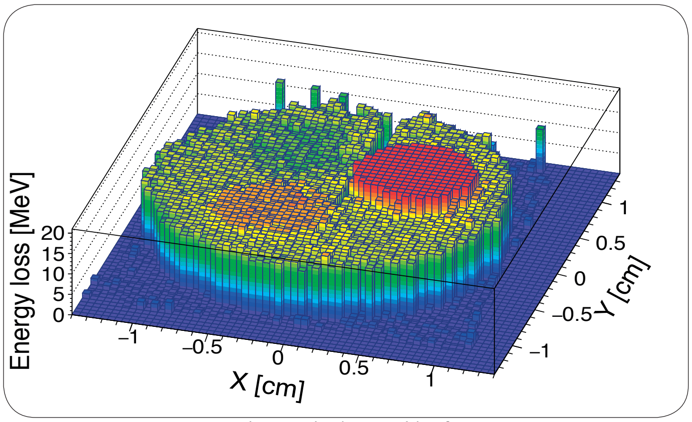

Figure 2. Proton energy radiograph obtained by firing 150 MeV protons through a sample of solid water with human body density-like inserts such as plastic (PMMA), bone and fat.

Ultra-fast photon detectors
Harry van der Graaf proposed in his ERC-ARG 'MEMBrane' a photon detector based on Micro Electro Mechanical Systems (MEMS) technology aiming at sub-ps temporal resolution. The difference between a traditional photo multiplier tube (PMT) and this novel detector is in the nature of their dynodes. A PMT has reflective dynodes, whereas this research is developing transmission dynodes that will be stacked on top of each other. This simplifies the configuration and reduces the size to the scale of a pixel chip (55 μm). As a consequence, the time response is improved and the sensitivity to magnetic fields is decreased. The main challenge is to fabricate ultra-thin transmission dynodes with sufficient Secondary Electron Yield (SEY) at low primary electron energy, *i.e.* a yield of four electrons at 500 eV. The need of realizing sufficient SEY of the dynodes resulted in three main research themes: theoretical simulations, fabrication of the dynodes and measurements of SEY with prototype membranes. Monte Carlo simulations are used to study the physics of electron-matter interactions and predict the SEY of the dynodes, using a low energy extension of GEANT4 package in collaboration with an industrial partner FEI. Data obtained with SEY measurements are used for model validation and to further develop the simulation code. The effects of surface termination on the electron affinity, an important parameter for the SEY, have been studied by Density Functional Theory (DFT) simulations. DFT results showed very promising termination candidates, such as hydrogen or alkali-oxide terminations.

In 2014 various crucial research collaborations have been established. Fabrication of the dynodes with MEMS technology takes place at the Delft Institute for Microsystems and Nano-electronics (DIMES). A first generation of transmission dynodes with a thickness of 15 nm has been successfully fabricated. Additional generations with improved recipes and different surface terminations are under study. Besides ultra-thin dynodes, thin films with different Silicon doping ratios have been produced for SEY measurements on top of a TimePix3 chip. As a side project, alternative all-ceramic grid structures have been processed in collaboration with IZM-Berlin to enhance the spark protection of our *Gridpix* gaseous detectors. Measurements with a scanning and transmission electron microscope have been done to study SEY of the dynodes at the Particle Optics Group at the Technical University of Delft. In addition, a dedicated setup for synchronous measurements of both the transmission and reflective SEY has been built and calibrated at Nikhef, and used to study the fabricated films and dynodes in more detail. Soft X-ray photoemission spectroscopy (XPS) at a synchrotron beam line at Brookhaven National

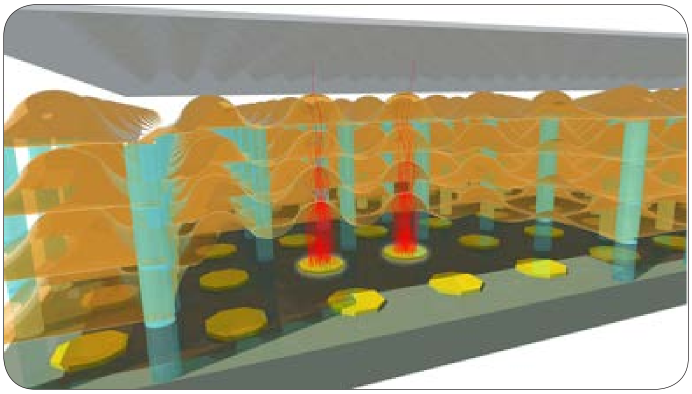

Figure 3. A stack of ultra-thin transmission dynodes forms a 'miniaturised' PMT on top of each 55 μm squared pixel of the readout chip at the bottom. A photoelectron escapes from the photo-cathode at the top, further electron multiplication results in a detectable signal that will be processed by the front-end circuitry in each pixel.

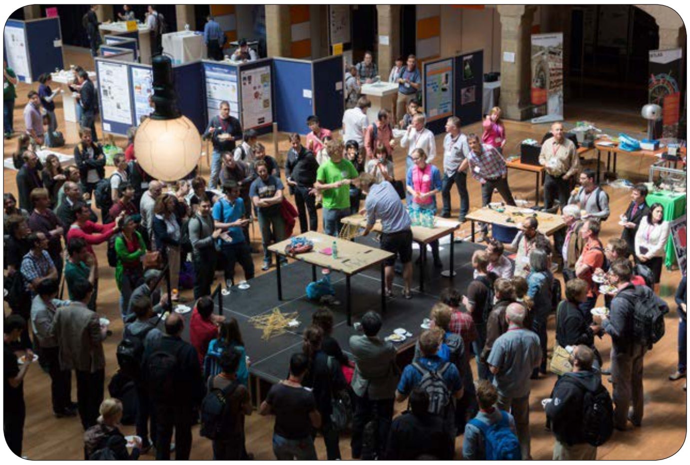

Figure 4. Impression of TIPP2014: building 'spaghetti' bridges between attendees.

Laboratory is essential to characterise the materials used in the dynodes and to understand the SEY performance of different terminations. Hence, low Silicon doped material was eliminated due to the severe charging effect while an important improvement in SEY has been established with hydrogen terminated dynode samples. The XPS results support our DFT predictions and provide validation of the Monte Carlo simulations.

Hosting the TIPP 2014 conference

The Technology and Instrumentation in Particle Physics 2014 (`www.tipp2014.nl`) conference has been hosted by Nikhef in *De Beurs van Berlage*, downtown Amsterdam from June 2–6. This new series of cross-disciplinary conferences on detector and instrumentation falls under the auspices of the International Union of Pure and Applied Physics (IUPAP). The program focused on all areas of detector development and instrumentation in particle physics, astroparticle physics and closely related fields like photon science, biology, medicine, and engineering. This medium-sized conference with 450 attendees brought together world experts from the scientific and industrial communities to discuss current work and to initiate partnerships that may lead to transformational new technologies.

Next to an exciting scientific program a number of social events were organised to stimulate interaction between participants, especially for newcomers to the field, and to challenge colleagues via problems encountered in their research. The program was solidly booked and highly appreciated by the participants. Various interactive events took place during the day: discussion sessions, a 'spaghetti' bridge contest, networking with industry, interactive theatre with installations, several physics demonstrations, and a chance to build an instrument from a scrapheap. In the evening, leisure activities in the historic center of Amsterdam included a pub-quiz, a conference dinner in the historic Heineken brewery, and a pub crawl, hearing about the history of Amsterdam and the forgotten Einstein-Rupp experiment, and the opportunity to play Arcade and board games with Nikhef director Frank Linde. Prof. Robbert Dijkgraaf gave an excellent outreach lecture for the general public about the frontiers of physics and 'What is it good for?'