Detector Physics
A specialisation in Computer Simulation in Science

Topics for Particle Detector Projects

(1) Machine-learning algorithms on Field Programmable Gate Arrays (FPGAs)
Scientific advisor: Dr. Marius Wensing
Machine Learning is a field of science which becomes increasingly relevant more in our life. It is used in a huge variety of applications, e.g. in object or speech recognition and chatbots like ChatGPT. While training these neural networks can be a rather slow process, often involving floating point operations and the use of graphic cards, the finally trained network is static and can be optimized to run on embedded systems with much less computational and power requirements.
In particle physics detectors, object recognition is important to distinguish between physics data of interest and background noise, which is typically required in the experiment's trigger systems. In these systems, only a very short time period is available to decide whether to keep or discard the data. The use of hardware-accelerated FPGA-based neural networks in the experiment's trigger systems is an emerging topic [1] in the HEP trigger community.
The project proposed aims for implementing a basic neural network for object recognition in an FPGA. First, the basic algorithms for the neural networks must be implemented in a hardware-description language (VHDL). The network will be trained on a computer using MATLAB and converted there to use it in the limited environment on the FPGA. Finally, a comparison between the PC-implementation and the implementation inside the FPGA will be performed, concentrating on computational accuracy and performance.

[1] Andrea Coccaro, Francesco Armando Di Bello, Stefano Giagu, Lucrezia Rambelli, Nicola Stocchetti. Fast Neural Network Inference on FPGAs for Triggering on Long-Lived Particles at Colliders. Mach.Learn.Sci.Tech. 4 (2023) 4, 045040, arXiv:2307.05152

(2) Scanning Tunneling Microscopy
Scientific advisor: Dr. Sebastian Schimmel
Through the method of scanning tunneling microscopy, students learn about the experimental approach to the investigation of structural and electronic properties of material surfaces with atomic resolution in direct and reciprocal space. Students acquire knowledge of fundamental relationships and concepts of solid-state and surface physics, such as the atomic lattice, reciprocal space, electronic band structure and state density, as well as scattering and quasiparticle excitations. These concepst will be illustrated, consolidated and deepened through the processing and analysis of data obtained in the experiment. Important methods of image and data processing such as the Fourier transform, symmetrization and fitting are tested and applied. The students will become familiar with the scanning tunneling spectroscopic detection of so-called quasi-particles by means of simulations. In this way, they learn about the investigationability of certain quasiparticles in solids, which are otherwise known from high-energy physics but have not been observed there so far. Characteristic properties of the quasiparticles typical of exotic electronic phases such as superconductivity or topological insulators are qualitatively considered.

(3) Online Software for the new ATLAS Pixel detector
Scientific advisor: Dr. Gerhard Brandt
Modern large particle detectors require extensive computing infrastructure to deal with data taking and calibration. Various layers of online software form a complex overall

system running across multiple interacting computing clusters. The proposed project will give a practical introduction to the employed technologies.

The Wuppertal ATLAS group is participating in the ATLAS experiment at CERN where the next generation of online software is currently under development for the Inner Tracker Pixel Detector [1] (and potentially other systems) which will be operated at the HL-LHC (High Luminosity Large Hadron Collider). At the lowest level, a Trigger and Data Acquisition system [2] has to be able to respond in time to a trigger rate of 1 MHz within a 10us latency. On top of this hardware-based sub-system, software-based reconstruction follows to achieve further rejection of undesired signals. Up to 10 kHz event data are sent into storage, summarizing information from hundreds of millions of input channels.

On the user side the system has to be able to handle simultaneous input from potentially hundreds of users spread around many physical locations. All user inputs have to be correctly orchestrated to get the system into the properly configured state for data taking or calibration. This requires modern distributed computing techniques. We are developing a system based on microservices technologies and related modern computing paradigms.

The project proposed allows a glimpse into the current state of development and exercise the operation of various components of the online software, as well as demonstrate the development workflow. The transfer task involves operating an emulator-based software setup that will demonstrate the detector calibration process, as well as exemplary addition of functionality to the existing setup. Four sub-tasks along the chain are defined:

a) The software lives in the code version management system Git and is compartmentalized into Docker containers. The first task will consist in checking out the software, starting and managing the various components.
b) On the user-facing side (frontend) it is planned to implement graphical user interfaces in the browser. An existing user interface will be operated and modified by the student to include new UI elements.
c) An emulated data taking run based on a software emulator will be started from the UI.
d) The results will be retrieved from the result database and displayed in the browser.
e) Operation on a real hardware single chip card containing and ITkPix V1 chip will be exercised. The results will be compared to the emulated results.

[1] ATLAS Collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS TDAQ System, https://cds.cern.ch/record/2285584

[2] ATLAS Collaboration, Technical Design Report for the ATLAS Inner Tracker Pixel Detector, https://cds.cern.ch/record/2285585

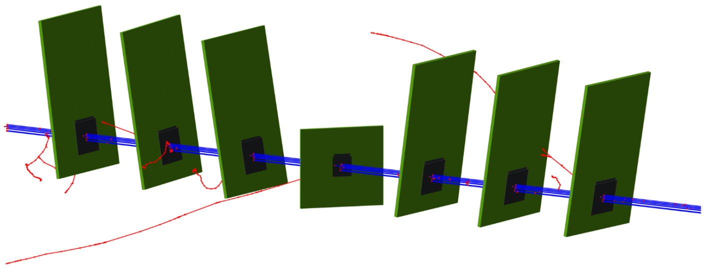
(4) Silicon pixel detector in a test beam – Simulation and Analysis

Scientific advisor: Dr. Paul Schütze

Silicon pixel detectors in high energy physics experiments typically serve the tracking of charged particles, among others for a determination of the particle momentum and the reconstruction of vertices.

In the development cycle of silicon detectors, detailed simulations as well as a thorough characterisation of detector prototypes via so-called *test beam experiments* play crucial roles. In a test beam experiment, multi-GeV particles are directed at the device under test (DUT), while determining the particle trajectory with another, well-known tracking detector. Comparing the reference trajectory with the detector signal allows for a determination of the spatial resolution and the detection efficiency of the DUT.

In this project, a test beam experiment is simulated using the semiconductor simulation framework *Allpix Squared* and the simulated data is analysed via the test beam reconstruction framework *Corryvreckan*. This will provide insight into the working principle and characteristics of silicon pixel detectors with software tools widely used in the community.



(5) Momentum resolution in silicon tracking detectors

Scientific advisor: Dr. Paul Schütze

Silicon detectors are applied in high energy physics for the determination of trajectories of charged particles, and with large tracking systems being located in strong magnetic fields, this allows for precise measurements of the particles' momenta. The resolution of the momentum measurement however depends on several parameters, such as the magnetic field strength, the detector geometry and the particle momentum itself.

In this project, the semiconductor simulation framework Allpix Squared is used to simulate the passage of particles in a simplified and configurable tracking detector. The simulated data is then used to reconstruct the particles' momenta and the corresponding uncertainty. Varying the detector layout as well as many other simulation parameters, the dependency of the uncertainty on these parameters is studied. What does the ideal tracker look like?

This project demonstrates some of the working principles of tracking detectors.