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1.1	01.01.2021	Sergey Kononov	Updates of BINP projects
1.2	03.01.2021	Alexander Barnyakov	Updates of BINP projects
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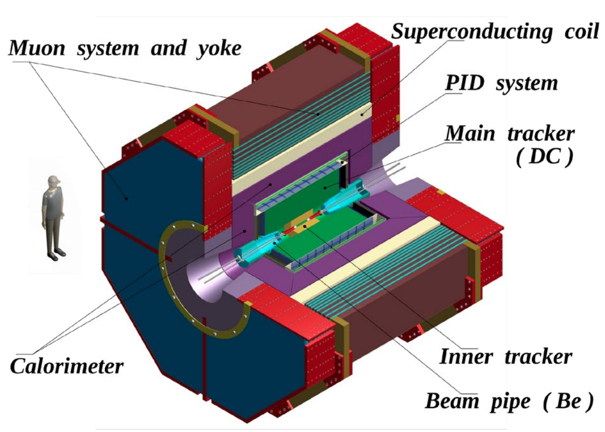
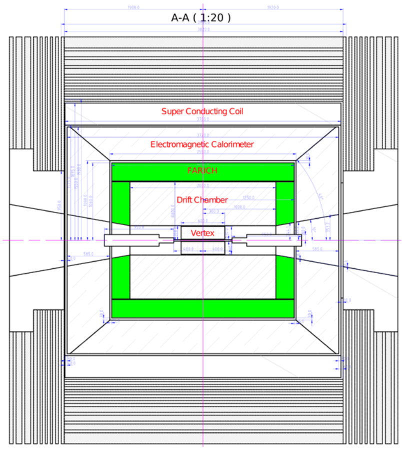
Particle Identification System for the Super Charm-Tau Factory

The future Super Charm-Tau (SCT) Factory has ambitious physics goals that require a challenging performance of the particle identification (PID) system. The figure below shows an overview of the current design of the SCT detector and a sketch of the reserved spaces for the sub-detectors. The PID system is going to be installed behind the main tracker and in front of the calorimeter. Its main goal is to achieve a μ/π separation of at least 3 standard deviations (s.d.) within a particle momentum range of 0.2 to 1.0 GeV/c. For momenta below 200 MeV/c, a sufficient μ/π separation can be performed with help of the inner tracker and the drift chamber. Above 1 GeV/c, however, the detection of muons will be done with the help of dedicated muon systems. The PID detectors are highlighted in green.





For that purpose, two different systems for PID have been proposed. One is based on the Ring Imaging Cherenkov (RICH) detector design containing a radiator with a low refractive index such as aerogel which allows it to acquire a full image of the Cherenkov cone. The main development of this system takes place at BINP in Novosibirsk. The other proposed design is based on the technology of

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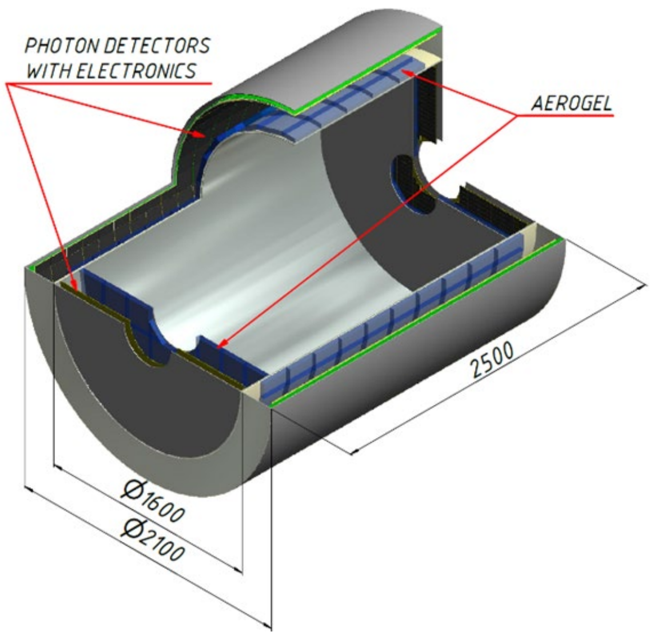
Detection of Internally Reflected Cherenkov light (DIRC). It contains a radiator of fused silica or another material with a high refractive index, in order to internally reflect the Cherenkov light to the rim where it is focused to the surface of highly sensitive photon sensors. Both detectors have to be designed for the barrel region around the interaction point as well as for the two endcaps, in order to guarantee a coverage of the full solid angle.

These complementary design approaches have certain parts in common, especially the front-end electronics (FEE) and DAQ system, but they have different granularity, number of channels and sensitivity to background, so that a design that combines both types in different regions of the phase space has the chance to outperform both individual designs in costs and performance. This is one main subject of the current studies.

The conceptual layout of the Focusing Aerogel RICH (FARICH) system for SCT is shown in the figure below:



The radiator of the FARICH consists of a stack of aerogel plates with different refractive indices. The variation in the refractive indices has the effect that the Cherenkov cone created in each layer is focused to the same ring position on the sensor plane and thus improves the detector resolution. There are, however, three major issues related to the FARICH development which are planned to be solved within this project: the relatively high threshold momentum for pions, the large number of photosensitive pixels, and the high dark-count rate (DCR) for Silicon Photomultipliers (SiPMs).

The design of the Focusing DIRC (FDIRC) detectors are based on previous developments for the PANDA experiment at FAIR. The figures below illustrate the current design of the Barrel DIRC (left) and Endcap Disc DIRC (right).

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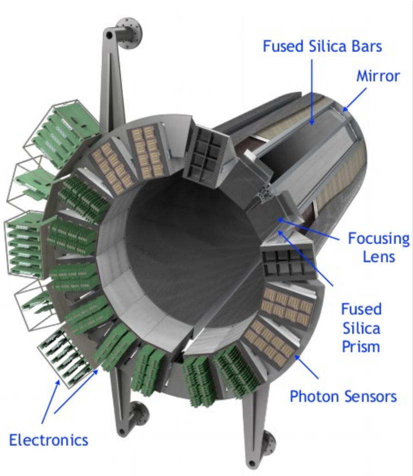
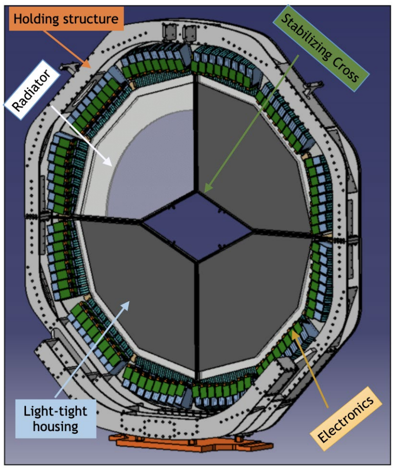
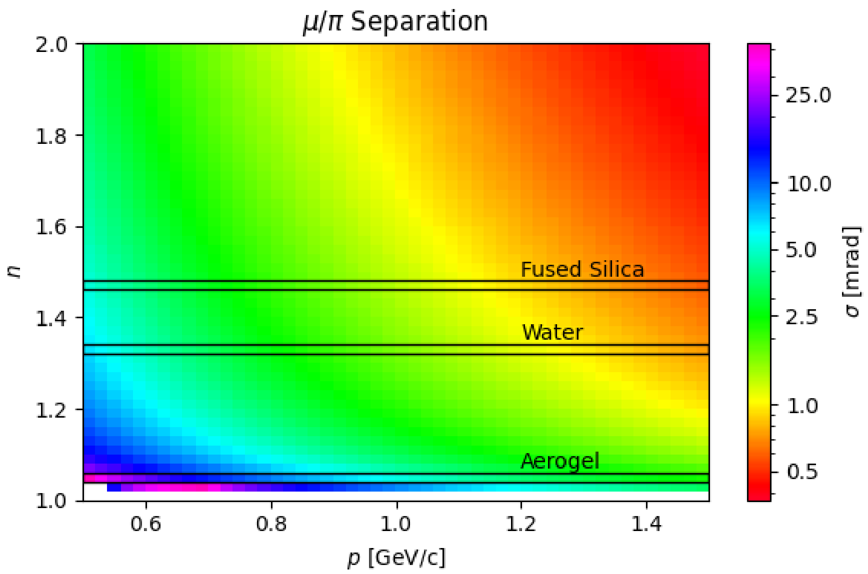




These detectors were mainly developed for identifying hadrons by providing an excellent PID for $\pi/K/p$ up to particle momenta of 4 GeV/c. Adopting this design for a sufficient μ/π separation is challenging because of the small difference in the rest masses of these two particle species. The two main limitations in resolution are related to the dispersion of the created Cherenkov light and to the smearing of the particle trajectory due to angle straggling of the charged particle when traversing the solid radiator material. Another drawback of a radiator with a large index of refraction compared to aerogel is the required angular resolution. In order to achieve a separation power of 3 s.d. for μ/π separation with an aerogel radiator, an overall detector resolution of around 2.5 mrad will be sufficient, whereas a much better resolution of around 0.7 mrad will be necessary for materials with high refractive indices such as fused silica as shown with an analytical calculation in the plot below:



Simulation Results for FARICH and FDIRC

Both detector designs were fully implemented into standalone simulation frameworks based on Geant4. The following figure shows the geometry of a FARICH (left) and barrel/endcap FDIRC (right) prototype.

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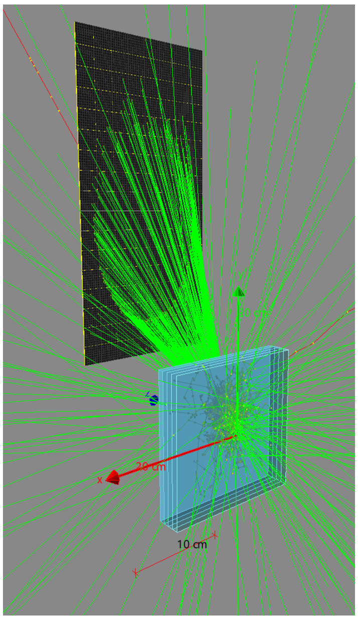
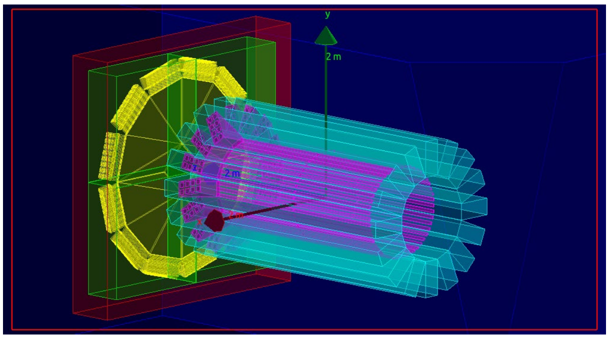
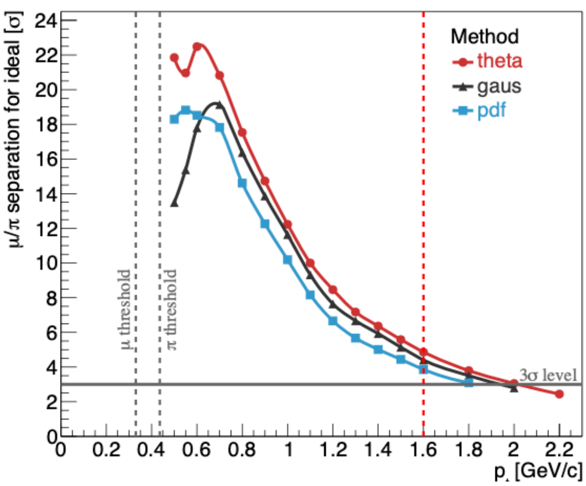
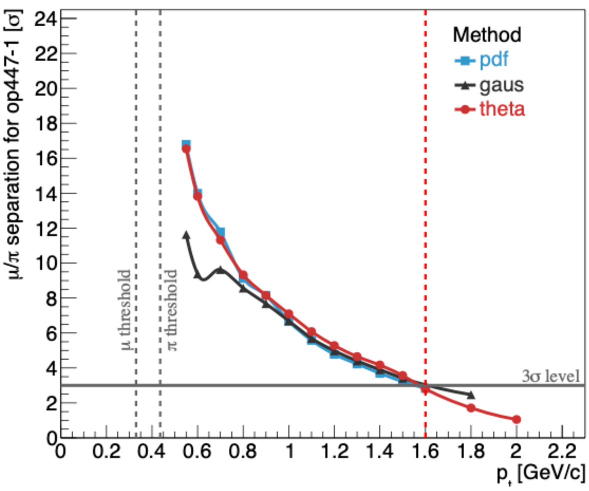




The simulations include all important optical and material parameters that are required to propagate particles and photons correctly. Each material and sensor efficiency were modeled according to measurements and data sheets. In both cases, reconstruction algorithms based on fully analytical arithmetic has been implemented. In the case of FARICH, three different approaches for the extraction of PID probabilities can be used: a radius-based reconstruction using a Gaussian fit, a likelihood method, and a reverse raytracing method that requires a transformation of the photon tracks into a local particle system. The figures below show the separation power of FARICH versus the particle momentum for all three reconstruction methods and two setups: for ideal 4-layer aerogel refractive index profile (left) and for a produced 4-layer aerogel sample (ID=op 447-3) (right). It was observed that for ideal 4-layer focusing aerogel Gaussian fit (gauss) and reverse raytracing (theta) methods give the better results than the likelihood (pdf) method, whereas for real 4-layer focusing aerogels with some imperfections in profile of the refractive index the difference between the methods is almost negligible, but the likelihood (pdf) and reverse raytracing (theta) methods are slightly better.





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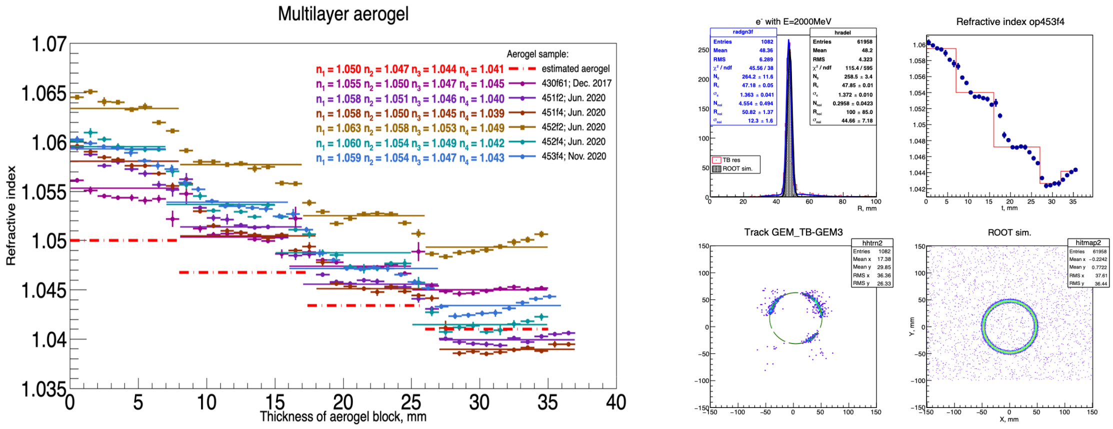
For both detector types, the Monte-Carlo simulations agree with measured data from various test beams. Missing parts in the Geant4 framework for SCT are currently still the magnetic field map and a realistic physics background. The implementation of both detectors into the common software framework Aurora has been started a few months ago and is progressing well. A parameterized model was used to describe the geometry and optical surfaces. The implementation of the reconstruction algorithms is currently in progress.

Test Beam Results for FARICH

Since 2018, the production of focusing aerogel Cherenkov radiators has been carried out in Novosibirsk continuously by BINP in collaboration with the Boreskov Institute of Catalysis (BIC). Several aerogel samples were tested in the FARICH prototype with a relativistic electron beam at the BINP test beam facility. The profiles of the refractive indices of various samples with a transverse size of 10x10 cm² are presented in the figure below (left panel), where the refractive index increases in upstream direction for providing a sufficient focusing of the Cherenkov light. The analyzed test beam results were then compared with Monte-Carlo simulations (right panel) showing a good agreement.



These results demonstrate that a single photon resolution (SPR) as low as 10 mrad can be achieved which is sufficient to provide μ/π separation of more than 3 s.d. at a momentum of 1.5 GeV/c.

Compact FEE for FARICH and FDIRC

New FEE has been designed at GSI for FARICH based on their customizable, inexpensive TRB3 platform. It can later be adapted also for a future single photon readout of the FDIRC design. It mainly contains an amplifier board with a size of 27x27 mm² and a TDC board. The amplifier board consists of a 14-layer PCB and is able to provide a gain of 30 for 64 channels in total. Its shape and connectors make it possible to directly couple it to SiPM 64-ch arrays PA3325-WB-0808 by KETEK. The 64 channels are digitized by a TDC board containing 2 TDC FPGAs and 4 FPGAs for threshold configuration. The internal TDC timing resolution is given as 10 ps. The SiPM signal shapes have been simulated for different input resistances and the results indicate a maximum amplitude of 22 mV for single photons which is large enough for the following discrimination and digitization stages. The designs of the amplifier (left) and TDC (right) boards are shown in the following CAD drawing:

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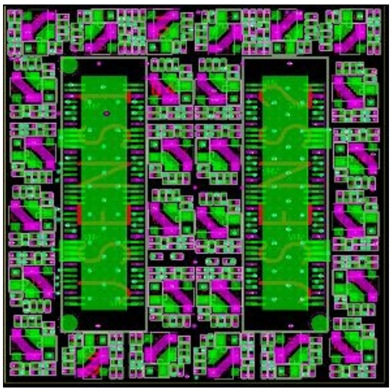
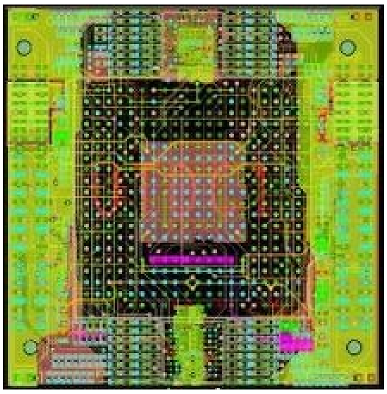
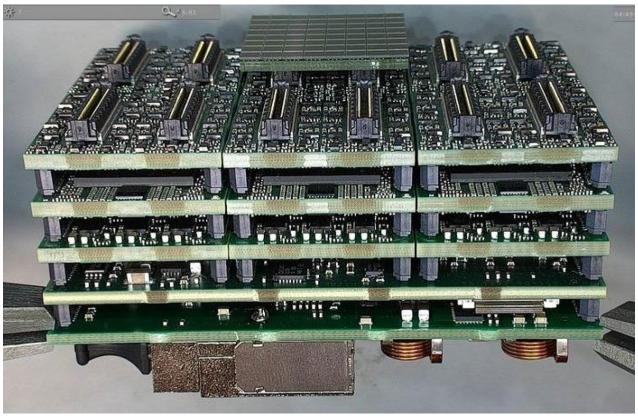




6 SiPM arrays together with amplifier-, TDC- and power-distribution-boards are plugged into one backplane board with dimensions 51x84 mm^2. The backplane board houses FPGAs for data concentration. Behind the backplane there is a board with DC-DC converters in order to provide the required power for the sensors, the amplifiers and FPGAs using a single power input of ~30V. The converters contain only air inductive coils to allow for an operation inside a magnetic field. Additionally, there are power, trigger, and clock connectors mounted to the converter PCB. Below, one can see a picture of the full setup including the backplane and the stack of all PCBs with one out of 6 KETEK SiPM arrays plugged in.



FARICH Prototype

A FARICH prototype to register a full Cherenkov ring has been constructed. The prototype is equipped with a SiPM array from KETEK containing 36 SiPMs and a liquid cooling system based on LAUDA which is currently under development. The FPGA-TDC based electronics will read out 2304 SiPMs in total. They will be produced at GSI and the testing of the full prototype setup is planned for 2022. A 3D sketch is presented in the figure below, showing the cooling pipes, air fans, and SiPM arrays attached to the readout boards.

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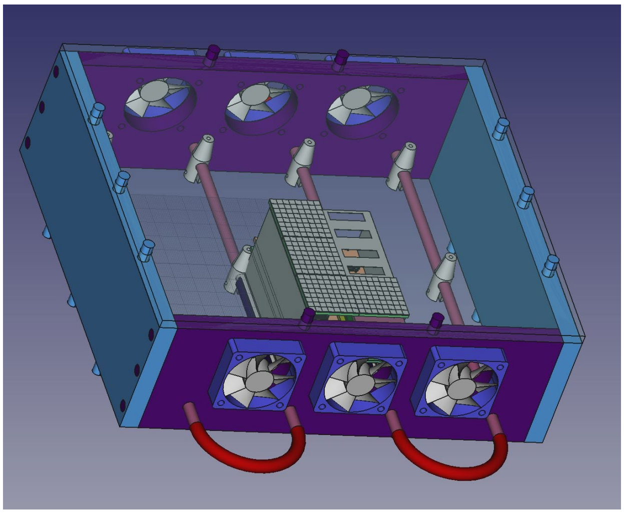
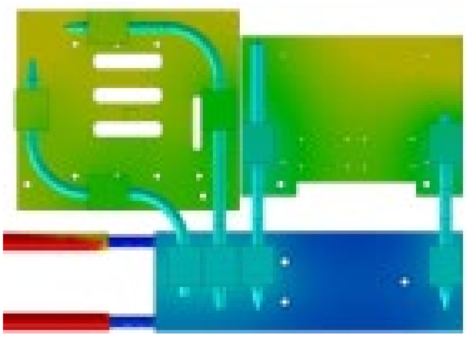
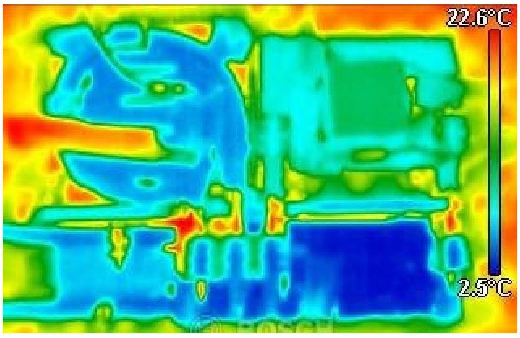


Five 4-layer focusing aerogel samples with transverse sizes 100x100 mm^2 were produced in 2020-2021. The preliminary beam test results of these samples verified a SPR of about 10 mrad, which is only 30% worse than expected for an optimum aerogel refractive index profile. Therefore, these samples are well suited as Cherenkov radiators for our future FARICH prototype tests with mixed hadron beams.

Cooling System for FDIRC Prototype

A first prototype of the FDIRC, containing a fused silica radiator with an attached Readout Module (ROM) and a readout based on TOFPET-2 ASICs from the company PETsys including a cooling setup, has already been constructed and operates currently inside the cleanroom of the JLU research group. The cooling system prototype contains a liquid cooling device from the company Huber, which allows a cooling temperature of up to -10°C, as well as heat pipes for establishing a thermal bonding between different heat sinks. The figure below compares our thermal flux simulation (left) with our measurement (right) taken by an infrared camera. The combination of simulation and experiment allows us to optimize future designs of cooling systems.





A photo of a similar setup is shown in the figure below. The hollow copper plates and the attached heat pipes are clearly visible. In addition to pictures with an infrared camera, several thermometer probes were connected to the various points on the plates to validate the IR-camera temperature calibration.

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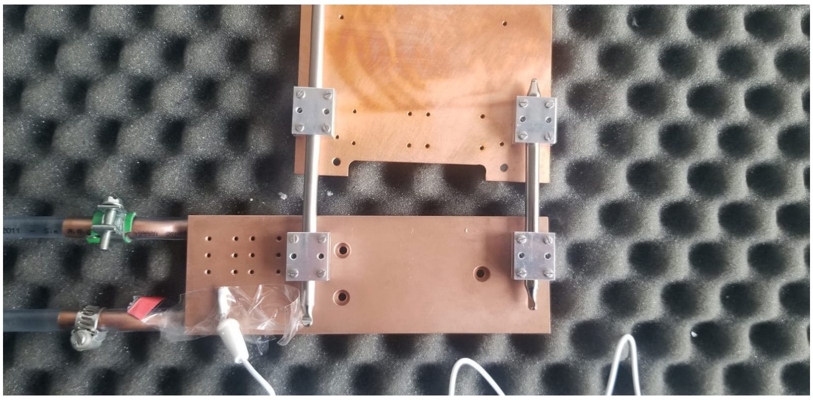
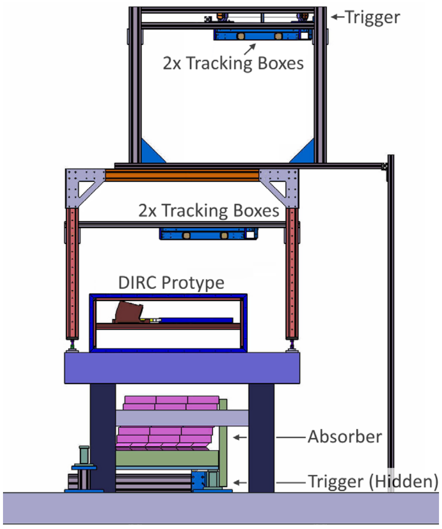
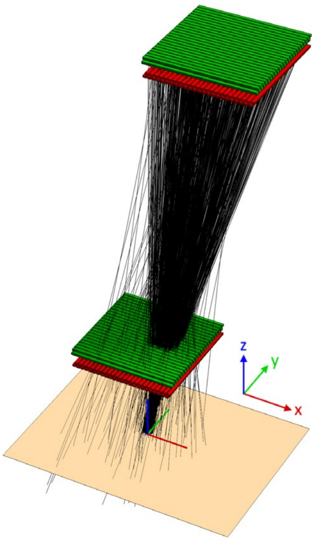


Giessen Cosmics Station for FDIRC Commissioning

In order to evaluate the real detector performance, a cosmic muon hodoscope called Giessen Cosmics Station (GCS) has been instrumented and tested successfully. It uses scintillator bars for the tracking of cosmic muons. Different reconstruction methods using simple track extrapolations and lookup tables have been designed, in order to optimize the performance to its limit. The figures below illustrate the setup and a bunch of muon trajectories tracked and reconstructed by the GCS in coincidence with finger scintillator counters in the horizontal x-y-plane on radiator height level.





Simulation results indicate a polar angle resolution of around 3 mrad and a position resolution of 4 mm which are comparable in precision to test beam setups we took at CERN in the past. Geant4 Monte-Carlo production was used to generate the distributions for the x-position and the polar angle as shown in the plots below. The results show the deviation of the reconstructed value from the Monte-Carlo truth. The sigma value from the Gaussian fit equals the achievable tracking resolution.

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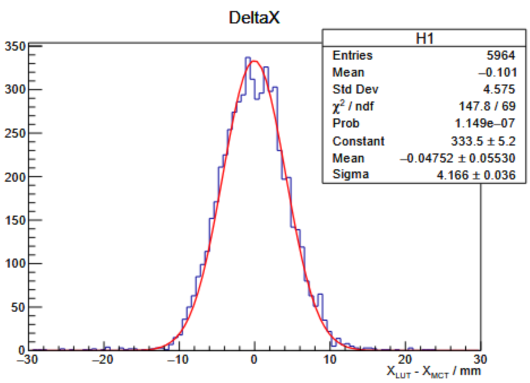
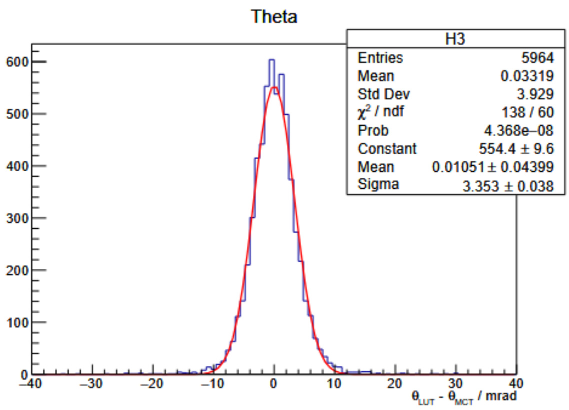
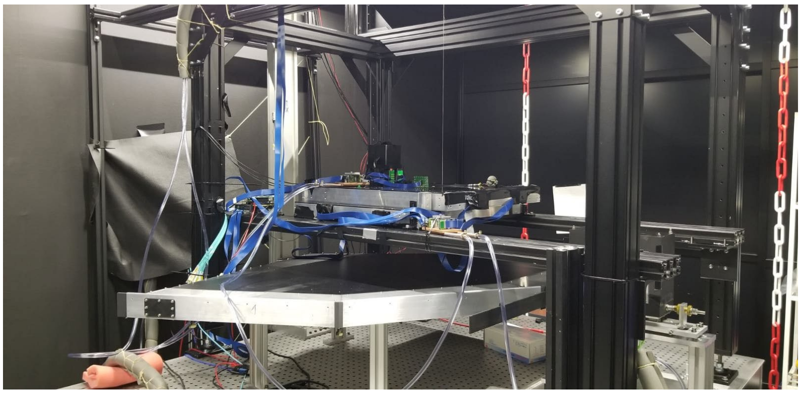
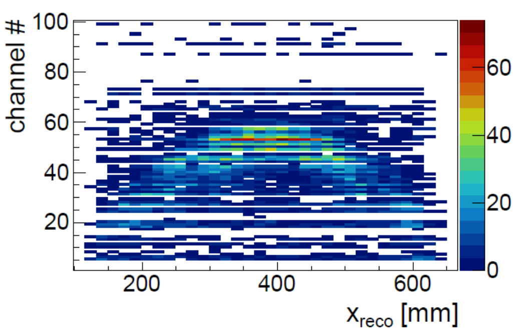


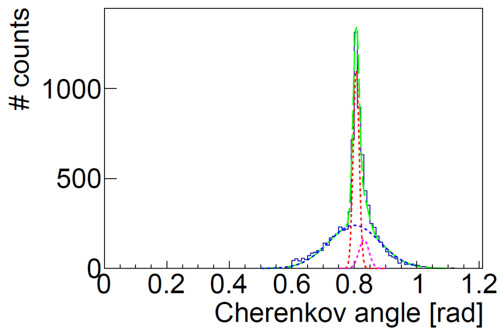


The FDIRC prototype is currently mounted on an optical table below the two required tracking boxes that contain small scintillation bars for track reconstruction. An additionally installed lead absorber above the lower trigger plate allows for the rejection of low-energetic muons with a threshold energy of around 700 MeV. This cut-off is required to ensure that all muons have a similar Cherenkov angle and to reduce effects from low-energetic particles. The following photo shows the DIRC radiator plate in combination with one ROM placed on an optical table. The whole setup is situated inside a dark, temperature-controlled clean room.



First results with cosmics muons have been obtained and show good agreement with Monte-Carlo simulations. The figure below shows an example of a measured hit pattern on the equipped photosensor for different particle positions and the reconstructed Cherenkov angle for a certain spatial cut. The results indicate an overall resolution of better than 8 mrad which is compatible with theoretical predictions and simulations. However, a new type of track reconstruction containing look-up tables is available and new type of track reconstruction containing look-up tables is available and will soon be tested with real data, in order to improve the results even further.





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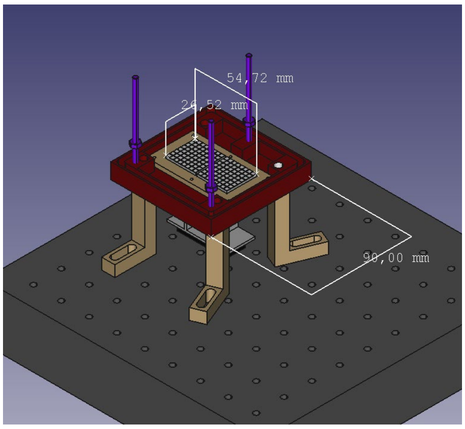
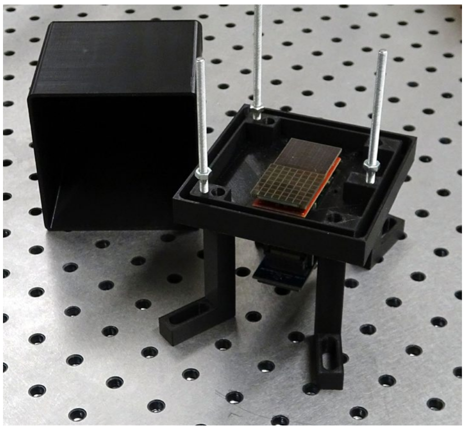
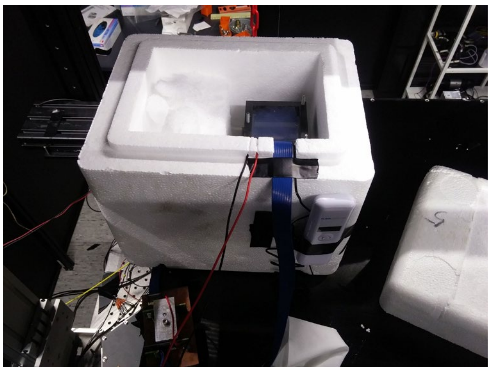
In addition to the large DIRC radiator, a second smaller setup for testing sensors and radiator prototypes is installed in the GCS. This setup is internally called Mini-GCS and allows the testing of several detector components on-the-fly by using the same readout electronics as the GCS. The dimensions and a photo of the produced design are shown in the following figure.

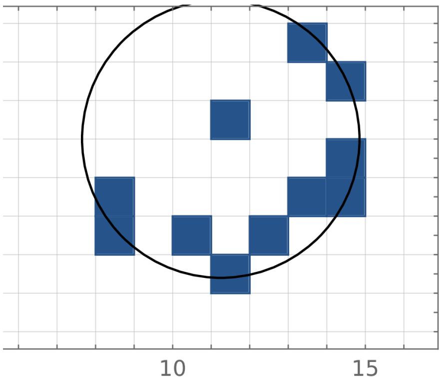




The Mini-GCS consists of a light-tight 3D-printed plastic box. The inner part of this detector contains adapters for the connection of up to 2 SiPM arrays with 8x8 sensors.

As shown in the figure below, the housing consists of an insulating Styrofoam mantle that allows for the cooling of the components with dry ice. First photon rings have been observed and will be studied further in the near future. An existing algorithm for identifying rings is already available and going to be improved during the following months.





The cooling is needed to run the SiPMs at low dark count rates. A newer setup has recently been installed which uses a continuously running cooling box instead of using dry ice that has to be exchanged frequently. The testing of the set-up has only started in January 2022, and we are awaiting results soon.

FDIRC Readout System

A new custom-designed PCB has been received by JLU. It is a combination of two rigid PCB parts that are combined by a flex PCB as shown in the following figure.

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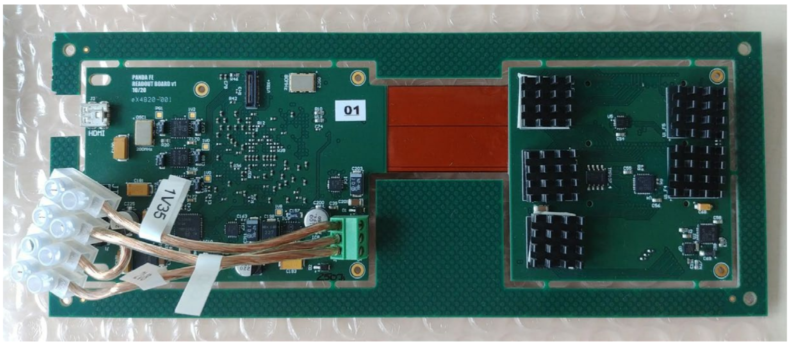
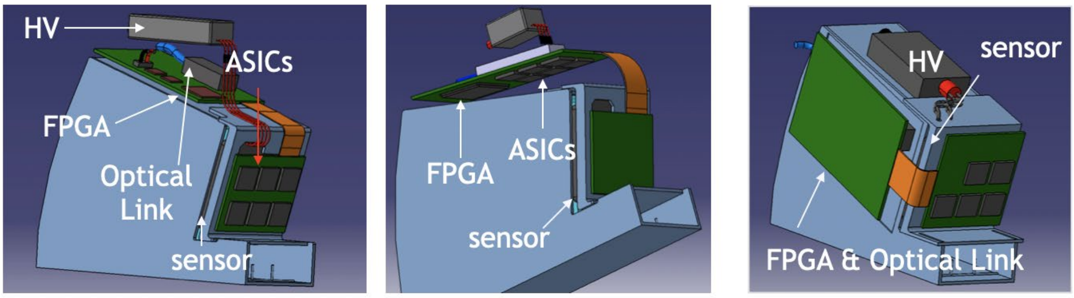


This PCB was designed to be mounted directly to an attached MCP-PMT. It can be bent around the focusing elements for saving space in the final detector. In total, three different options have been developed and can be used depending on the design of the final detector and the available cooling concept.



The digitization happens on the right part of the PCB (in the previous figure) which contains the currently used TOFPET-2-ASICs from the company PETsys. Each ASIC is used to digitize 64 MCP-PMT channels. The digitized signals are sent via the flex part to the readout board containing an FPGA and a VTRX+ optical connector, which sends the concentrated serial information to a DAQ computer. For the power connection, FEAST modules from CERN are going to be used, which are DC-DC converters that supply the various required voltages. It is planned to test this PCB in combination with an adapted cooling design within the coming months in our GCS. For testing purposes, a design as shown below will be used:

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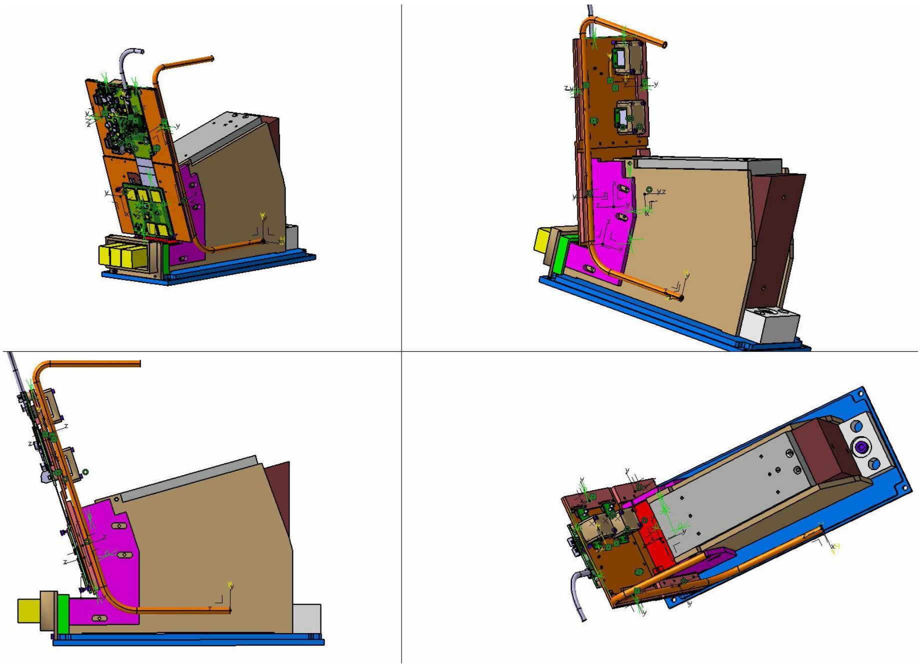

The PCB will be mounted without bending it, in order to use the existing cooling system prototype without applying too many changes. This new design is currently under construction in the mechanical workshop and will be ready for operation in the beginning of 2022.

Dispersion Correction for FDIRC

One major issue faced during the optimization of the FDIRC design is the mitigation of dispersion, as this is by design the major contribution to the overall resolution. There are actually three possibilities to reduce the chromatic error. The first one is to optimize of the accepted wavelength interval of the photocathode of the sensors and the second one is the use of optical filters to reduce the accepted wavelengths. The plot below shows an analytical calculation of the expected detector resolution (single photon resolution divided by hit count) as a function of the minimum and maximum accepted Cherenkov photon wavelengths. For the expected number of hits, a radiator thickness of 2 cm and a detection efficiency of 5% were assumed which is close to the current detector design. Three wavelength intervals are labeled with the related photo cathode names of the company Photonis that produces sensitive MCP-PMTs.

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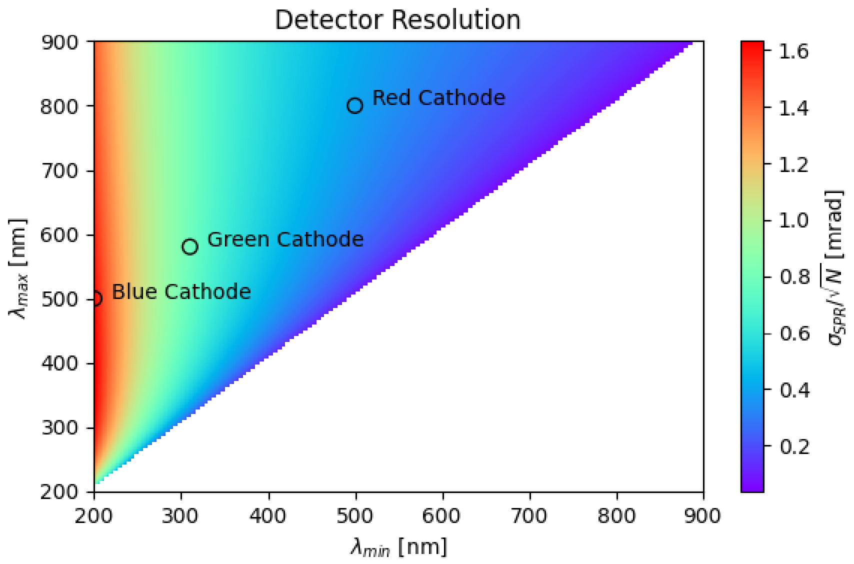
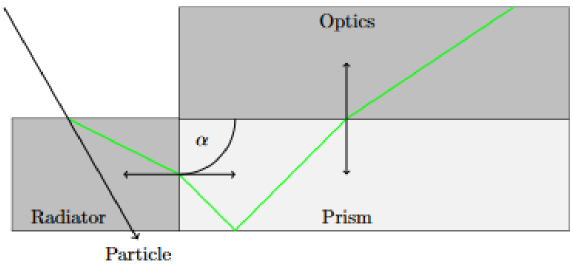
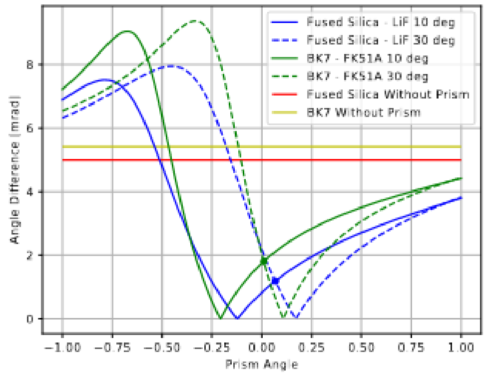


A photo cathode, that is sensitive in the red spectrum, leads to significantly smaller smearing compared to a green or a blue one. However, it turned out that these types of cathodes are significantly less radiation hard and relatively expensive.

A third and more powerful way to reduce chromatic effects is the use of optical elements with different refractive indices for chromatic corrections. The working principle is illustrated in the following figure. The left panel shows the photon entering from the left and being refracted at the two prism surfaces. The obtained results with the maximum achievable improvement for different material combinations are shown in the right panel. Each graph represents the angle difference between two photons with 300 and 400 nm for different polar angles of the primary particle. As a result, an improvement of a factor of 2 in the resolution seems to be obtainable with this 2-component setup.





An optimizer was then designed to study the optimum parameters in two dimensions. In the next step, the performance increase has to be simulated in 3D. For that purpose, a dedicated Geant4 framework has already been set up to evaluate the performance of DIRC optics. The left panel of the following figure illustrates a new type of focusing element for the endcap part of the DIRC detector containing two materials (light and dark blue in the figure below) for dispersion correction which has been developed for this project. The right panel shows the focusing position as a function of the angle of incidence (solid blue line) and the width of the projection of the Cherenkov cone on the sensor (dashed blue line) computed with the optimizer.

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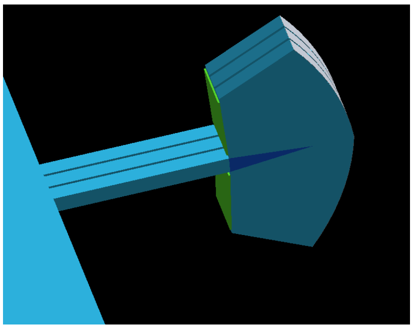
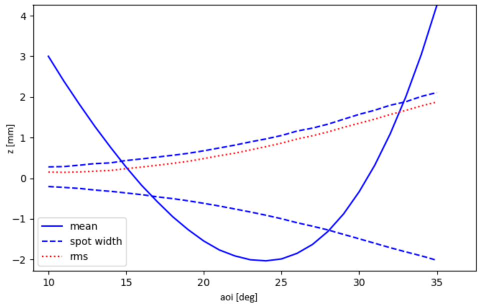
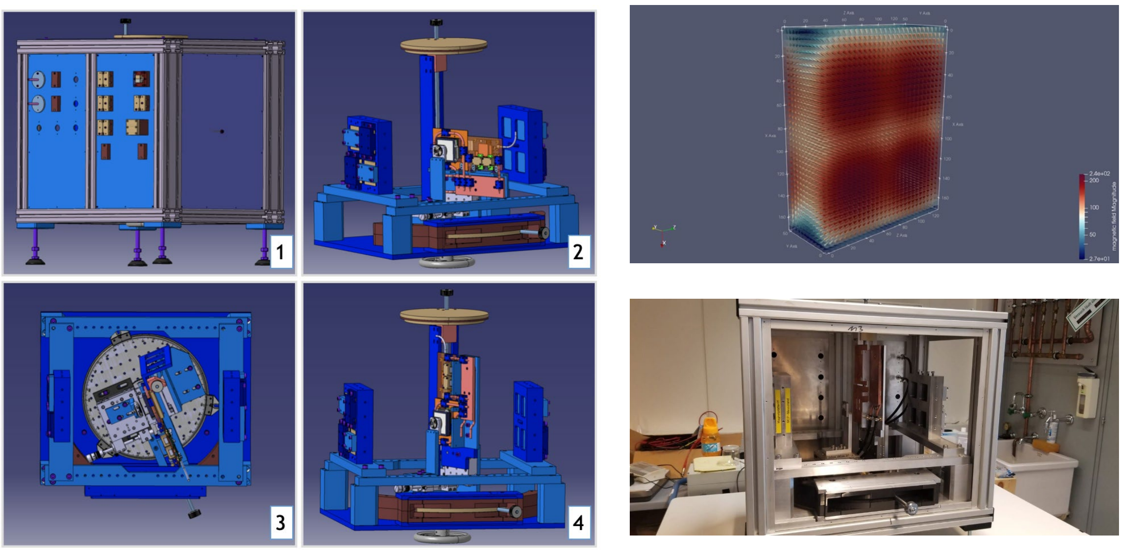




The new design turns out to be already a huge improvement compared to previously used focusing optics. However, there is still optimization required and many other ideas of improving the geometry and optical quality of the DIRC can be developed in the coming months as for instance replacing the focusing elements with lenses and small expansion volumes.

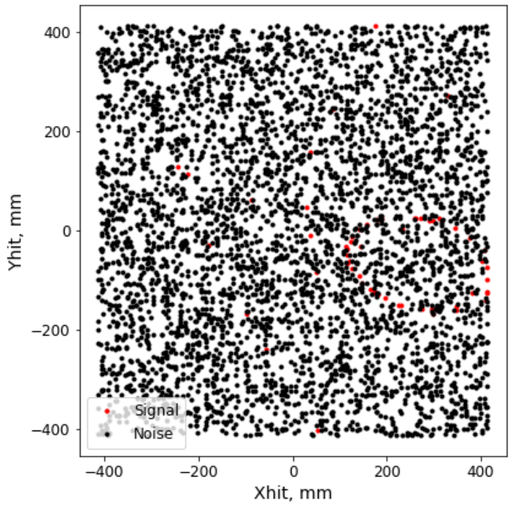
FDIRC Sensor Testing Box

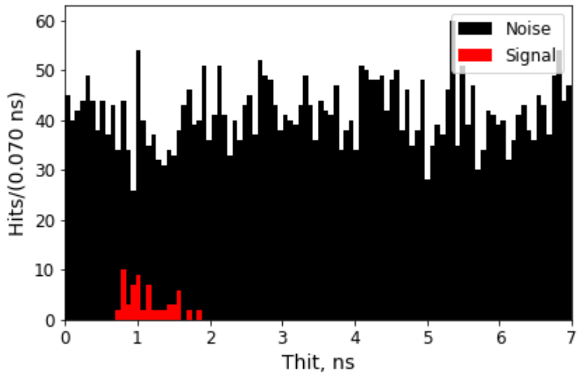
For dedicated testing of various detector components, a new light-tight testing box for SiPMs and MCP-PMTs was designed at JLU Giessen. It offers the unique possibility to install strong permanent magnets inside the box. The strength of the magnetic field can be varied by changing the position of the magnets relative to the readout electronics and sensors. Simulations and measurements with a hall probe have shown that a field strength of up to 250 mT can be achieved which is sufficiently high to study the performance of certain detector components. It is further possible to rotate the sensors relative to the magnetic field lines, in order to adjust the setup according to the design of the planned SCT environment. The following figure includes a 3D sketch from several perspectives as well as a photo of the current setup excluding sensor and FEE and related the obtained simulation results.



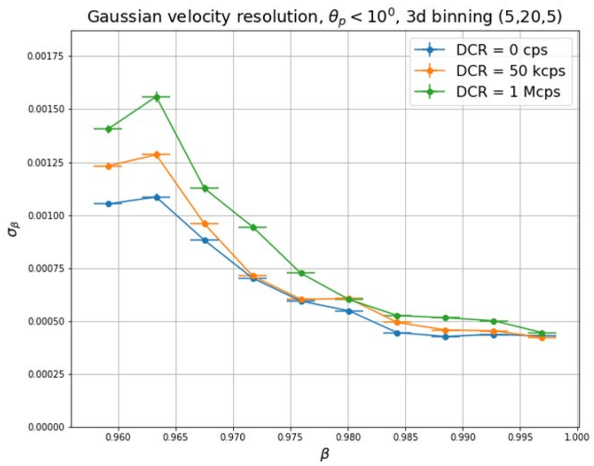
FARICH Reconstruction with Neural Networks

The BINP group works on improving the reconstruction algorithms for the FARICH detector. The main challenge of the high luminosity SCT experiment is coping with a high dark-count rate (DCR) background from SiPMs that can be as high as 10^6 cps/mm^2 for irradiated sensors. The only track-based reconstruction approach that has been shown to be robust with that high background level so far is an algorithm employing Artificial Neural Networks (ANN). The work is still in progress. The following pictures show simulated signal (Cherenkov photon hits) and dark counts plotted in the spatial coordinates and in time for DCR of 10^6 cps/mm^2.





From the figures above the level of difficulty can be estimated. The plot below demonstrates the particle velocity resolution vs velocity in FARICH for particles close to normal incidence by means of the ANN reconstruction algorithm for different levels of DCR.



One can see that the resolution deteriorates for higher DCR. However, even for 1 Mcps/mm^2 the obtained results are still sufficient to achieve the desired separation power.

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