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Electromagnetic calorimeter for the HADES@FAIR experiment


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ABSTRACT: An electromagnetic calorimeter (ECAL) is being developed to complement the dilepton spectrometer HADES currently operating on the beam of the SIS18 heavy-ion synchrotron at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany. The ECAL will allow the HADES@FAIR experiment to measure data on neutral meson production in heavy ion collisions in the energy range of 2–10 AGeV with the beam of the future accelerator SIS100@FAIR. The calorimeter will also improve the electron-hadron separation of the spectrometer, and will be used for the detection of photons from strange resonances in elementary and heavy ion reactions as well. The calorimeter will consist of 978 modules divided into 6 sectors, and it will cover forward angles of $16^\circ < \Theta < 45^\circ$ and almost full azimuthal angle. Each module consists of a lead glass Cherenkov counter, photomultiplier, HV divider and an optical fiber. A dedicated LED based system being developed to monitor the stability of the calorimeter is discussed. Various prototypes of front-end electronics are presented and the achieved energy and time resolution determined using pulses from a pulse generator and a real detector signal induced by LED pulses and cosmic muons is shown as well.

KEYWORDS: Cherenkov detectors; Calorimeters; Front-end electronics for detector readout
1 Physics background

The High-Acceptance DiElectron Spectrometer (HADES) located at GSI Darmstadt, Germany is focused on dielectron emission studies in few-GeV nucleon-nucleon [1, 2], proton-nucleus [3], and nucleus-nucleus collisions [4]. The HADES is currently operating on the beam line of SIS18 accelerator (cave B) with available energy range up to 4.5 GeV for protons and 1 AGeV for heavier nuclei up to uranium. A new accelerator SIS100 is being built within the Facility for Antiproton and Ion Research (FAIR) next to GSI and will enable to further accelerate protons up to 29 GeV and heavy nuclei up to 2.7 AGeV (uranium). The HADES spectrometer will be after the construction of the FAIR moved to the common cave with the newly build spectrometer CBM (Compressed Baryonic Matter). The physics program of the HADES@FAIR is based on the measurements with the accelerated beams of protons and heavier ions of energies up to 10 AGeV.

The HADES spectrometer is composed of the following detectors: a diamond start detector (START), a Ring Imaging Cherenkov detector (RICH), four sets of Multiwire Drift Chambers (MDC), a superconducting toroidal magnet (ILSE), a scintillator based time-of-flight wall (TOF)
and the RPC wall built from Resistive Plate Chambers, a pre-Shower detector (SHOWER) and a Forward Wall detector (FW). The spectrometer is divided into six sectors covering the polar angle $18^\circ < \theta < 88^\circ$. The detailed spectrometer description can be found in [5].

The electromagnetic calorimeter (ECAL) will enlarge the experimental possibilities of the HADES spectrometer by focusing primarily on gamma pairs coming from meson decays (photons cannot be measured in current HADES setup). This will enable precise determination of meson production cross-sections. The knowledge of these cross-sections will allow to properly account for corresponding dilepton yield from Dalitz decay of neutral mesons in the energy regime of the SIS100 beam, revealing other possible non-trivial sources of dileptons. Moreover, the investigation of $\omega$ production via the decay channels $\pi^0\pi^+\pi^-$ and $\pi^0e^+e^-$ can be done combining the two photon detection in the ECAL calorimeter with a charged particle detection in the rest of the HADES spectrometer. Last but not least, great interest in the photon measurements is coming from the HADES strangeness program studying mainly neutral $\Lambda(1405)$ and $\Sigma(1385)$ resonances in elementary and heavy ion reactions.

All these goals can be reached by replacing the HADES SHOWER detector located at forward angles ($18^\circ < \theta < 45^\circ$) with an electromagnetic calorimeter based on lead-glass modules. Improvement of the electron/pion separation at large momenta over 400 MeV/c is an important bonus offered by the planned electromagnetic calorimeter (at lower momenta a sufficient electron/hadron identification is provided by the RICH, RPC and TOF detectors already available in the current HADES setup).

## 2 Calorimeter design

### 2.1 Calorimeter layout

The basic calorimeter concept was determined by the current HADES layout (six separated sectors, space available behind the RPC detector) and by the lead glass crystals borrowed from the OPAL experiment [6] for free. Choice of the lead glass of given dimensions determined also the basic physical properties of the calorimeter (energy resolution not better than 5% at 1 GeV, the value achieved in the OPAL experiment). An energy resolution of 6% was chosen as a target value, although the simulations performed show the energy resolution of 9% as a still acceptable one.

The calorimeter will consists of 978 modules divided into 6 sectors (same as the HADES setup) and will replace the current Pre-Shower detector. The calorimeter will cover the area of $8 \text{ m}^2$ corresponding to the polar angles between $16^\circ$ and $45^\circ$ and almost full azimuthal angle (except the slots between the sectors). The total weight of the active part of the detector will be about 15 tons. A dedicated mechanical support structure has been designed to accommodate all the modules leaving the possibility of substituting a single module without moving the neighboring ones. The calorimeter will be placed on rails using ball-bearing based guidance, and it will be possible to displace it along the axis of the beam, to allow for accessing to the other HADES detectors. More details can be found in figure 1.

### 2.2 Calorimeter module

Each module of the electromagnetic calorimeter will consist of a lead glass, a photomultiplier with a high voltage divider, an optical fiber and a brass container, see figure 2. Lead glass is of a
Figure 1. Calorimeter layout — front view (left) and side view in pulled out state, current HADES setup being on the right (right).

Figure 2. Parts of the calorimeter module equipped with a 1.5 inch EMI photomultiplier (left), 3 inch photomultiplier with optical fiber and guiding ring (right).

CEREN 25 type with refractive index of 1.708, radiation length $X_0 = 2.51 \text{ cm}$ and Molière radius of 3.6 cm. Glasses have dimensions of $92 \times 92 \times 420 \text{ mm}^3$ and are covered in white TYVEK 1060B paper to enhance the light reflection on the surface. The photomultiplier is connected on one side of the glass crystal using optical grease Rhodorsil paste no. 7. The optical fiber of CERAMOPTEC multimode type is laid alongside the photomultiplier in direct optical contact with the glass on one side and standard LC connector on the back side of the module (the fiber will transmit light pulses for calibration purposes). The detector parts are held together by a brass can with a wall thickness of 0.45 mm and an aluminium cover on the back.

Most of the calorimeter modules will be equipped with the EMI 9903KB photomultipliers from the former MIRAC (WA98) detector [7]. More than 600 pieces were tested via measuring the dark current without any scintillator at first and later on with a small NaI(Tl) scintillator and a radioactive source to check the photomultiplier gain. The 3 inch Hamamatsu photomultipliers R6091 are planned to be used for the remaining $\sim 400$ pieces. Dedicated high voltage dividers were developed and manufactured for these photomultipliers, extensive set of tests showed that they are fully comparable with the original Hamamatsu dividers.

Due to the budget constraints and high price of the 3 inch Hamamatsu photomultipliers the 1 inch photomultipliers Hamamatsu R8619 are being tested as a possible replacement. The first results of the tests are mentioned in section 5.
The high voltage power supply system will consist of CAEN SY1527LC HV crates with 24-channel A1535 cards providing a voltage up to 3.5 kV and a current up to 3 mA per channel. Control of the high voltage will be done remotely using the EPICS control system [8].

2.3 LED based monitoring system

The LED based system is planned for calibration and stability monitoring of each single calorimeter module. Short light pulses will be guided to each module using an optical fiber of CERAMOPTEC multimode type connected to the LC connector on the rear side of each module. The length of the pulses is set in order to induce the same photomultiplier pulse shape as for cosmic muons, see figure 3 (left). A LED will be driven by a dedicated circuit, which will allow remote control of the pulse amplitude and frequency, and will also have a feedback control over the amount of produced light and a temperature stabilization using Peltier elements. Produced light pulses will be equally divided into the fibers in an optical device. The prototype with 10 fibers can be seen in figure 3 on the right.

3 Simulations

3.1 GEANT3 implementation

The performance of the electromagnetic calorimeter was simulated in order to demonstrate its benefits for the HADES spectrometer. The physics cases studied were modelled in the UrQMD model (Ultrarelativistic Quantum Molecular Dynamics) [9]. The basic ECAL module geometry was implemented in the HGeant code (the GEANT3-based simulation framework used by the HADES collaboration) [5] to model detector response. Various geometries of module positions and dimensions were tested in order to find a compromise between occupancy and number of channels. No frames and support structures were implemented in the simulated geometry so far.

3.2 Tracing of Cherenkov photons

The simulation of the lead-glass module response was split into two parts: shower development in a module (production of secondary particles and Cherenkov photons), and transport of Cherenkov
photons within a module (modules are optically isolated). As the transport of Cherenkov photons is a complex process involving absorption, reflection and refraction, and is not described by GEANT3 correctly, a single standing code for transport of Cherenkov photons developed by M. Prokudin was used [10]. Thus, the development of an electromagnetic shower and the Cherenkov photon production is performed by GEANT3, whereas the Cherenkov photon transport is delegated to a stand-alone program. To fasten the calculation a look-up table approach was used for photon transport.

3.3 Occupancy considerations

The occupancy of the calorimeter cells was studied on the case of the Ni + Ni collisions at 8 AGeV and impact parameter $b$ smaller than 1 fm, which should be the highest possible multiplicity event studied with the HADES setup at SIS100. Figure 4 (left) illustrates the event-averaged calorimeter cell occupancy using a cut on minimal deposited energy larger than 15 MeV. Squares correspond to the centers of the calorimeter modules. In the investigated conditions a highest occupancy of 0.8 is observed for the modules in the two innermost rows.

An occupancy of 0.8 might be a limiting factor of the detector and thus different geometrical arrangements are studied. One scenario is to cut the innermost modules into four separated pieces; then the cell occupancy would decrease to 0.4.

Another approach can be a change of the innermost cell inclination with respect to the direction of the incoming particles in order to minimize primary particle cross-talk between the neighbouring cells. The orientation of the cells in opposite sectors with respect to the beam axis can be seen in figure 5 (left). The 3D arrangement of the calorimeter cells can be seen in figure 5 (right).

3.4 Electron-pion separation

The possibility of measuring energy deposits in the ECAL detector, coupled to the track momentum measurement in the rest of the HADES spectrometer, has been shown to enhance the electron (positron)-pion separation in the detector for higher particle momenta ($p > 400$ MeV/c) [11, 12].
Figure 5. Modules layout in the vertical plane along the beam axis (left). The 3D arrangement of the calorimeter modules (right).

Figure 4 (right) shows the ratio between the energy deposited by a particle in the calorimeter and the momentum measured by the HADES tracking system, $E_{EMC}/p$, for electrons (empty histogram) and pions (filled histogram), with momentum between 900 MeV/c and 1 GeV/c, and impact parameter smaller than 2.5 fm. The separation capability granted by the presence of the ECAL measurement is apparent.

3.5 Diphoton measurements

To investigate the feasibility of the $\pi^0$ and $\eta$ reconstruction, events coming from the Pluto generator [13] were processed by the reconstruction algorithm of the entire HADES setup, with the calorimeter simulation included. Photon pairs have been formed as all possible combinations of photons identified by the detector. The expected combinatorial background has been modelled pairing photons produced in different events, and normalized to the high-mass tail of the observed photon pairs distribution ($M > 620$ MeV/c$^2$). Results for $\pi^0$ and $\eta$ in Ni + Ni case can be found in figure 6.

4 Electronic read-out

The following parameters have been assumed for the detector signals: rise time of 3 ns, falling time of 50 ns, signal to noise ratio $> 12$. The total dynamic range is from 50 mV up to 5 V with an energy measurement accuracy of 5 mV. The expected hit rate is up to 10 kHz/channel, and the required time resolution is 500 ps. To pre-process the input signal from the photomultiplier two concepts of front-end boards are being developed at the moment.

4.1 Cracow-design front-end board

The 8-channels front end board based on a separate time and amplitude measurement was developed at the Smoluchowski Institute of Physics of the Jagellonian University at Cracow. The front-end board splits the input signal from the photomultiplier into a fast and slow path. The fast path is based on a fast discriminator and delivers the signal directly to the TRBv2 (Trigger
and Readout Board version 2) [14] for time measurement. The slow path shapes the signal and delivers it to a fast sampling ADC addon board designed originally for the HADES Pre-Shower detector. This addon board operating at 20 MHz with 10 bit resolution is attached to a TRBv2 for an amplitude measurement.

Thresholds on the Cracow front-end board can be set separately for each channel via the TRB connection. Various combinations of the shaping time and gain were tested in order to reach the best energy and time resolution of the read-out system. Pulser signals with 10 ns width (FWHM) and 5 ns rise time resulted in 0.6% energy resolution and 100 ps time resolution. Energy resolution of 3.6% and the time resolution of 150 ps were obtained using LED pulses introduced to the lead glass and measuring the response of the module. First measurements with cosmic muons showed energy resolution above 8%. Examples of the front-end board energy resolution measured with a pulser are shown in figure 7.

4.2 PaDiWa based front-end board

The second scheme developed for preprocessing of the photomultiplier pulse is based on a charge to width (Q2W) conversion. The PaDiWa board (PandaDircWasa) [15] is used, the front part of the board is adapted and a modified Wilkinson ADC circuit [16] is implemented in a FPGA (Field Programmable Gate Array). The signal path consists basically of a capacitor, which collects the charge, and a dedicated circuit for its discharge via a current source. The FPGA based TDC with very precise time measurement (~ 12 ps RMS) is used to measure the time to discharge. The advantage of this approach besides the precise charge measurement is a fast crossing of zero, and hence low dead time of the channel. In addition, this method of discharging a capacitor works as an automatic baseline restorer, since a charge equivalent to the input charge is injected with the opposite sign.

The modified board was called PaDiWa AMPS and it is developed following the COME&KISS concept, thus Keep It Small and Simple by using Complex Commercial Elements. A first prototype demonstrating the charge to width conversion idea was successfully tested. A wide range of tests of the complete PaDiWa based prototype are planned for the near future.

Figure 6. Diphoton invariant mass spectra reconstructed in Ni + Ni collisions at 8 AGeV beam kinetic energy (black histogram), combinatorial background (blue histogram) and signal after background subtraction (red histogram) (left). The $\eta$ meson signal of the diphoton invariant mass spectrum (right).
The general purpose Trigger and Readout Board (TRB) version 3 [17] was developed for the HADES, PANDA experiments (Barrel/DISC-DIRC and Straws) and the CBM experiment (RICH, TOF, MVD readout) and is now foreseen as the digitizing board also for the calorimeter described here. A high rate, multi-hit TDC providing a superior performance in terms of time precision (< 20 ps RMS between two channels) will be used for the time measurement. The main functionality of the TRBv3 is the high precision TDC realized in FPGAs. The board also provides a high bandwidth DAQ functionality with data transfer capabilities up to several hundred MByte/s and can serve up to 256 detector channels. The digitizing board controls the parameters set on the front-end boards by separate slow control lines.

5 Tests of the modules using cosmic muons

Cosmic muons were used to study energy resolution of modules as well as of the front-end boards. The calorimeter modules were placed vertically and a coincidence signal from two 2.5 cm thick plastic scintillators with dimensions $8 \times 8 \text{ cm}^2$, one placed above and the other below the module, triggered the muons, see figure 8. One muon induced event per five minutes was measured on average.

The energy resolution of the modules was measured using three different systems (CAMAC based DAQ, oscilloscopes with histogram function and with developed front-end boards). Modules equipped with 1.5 inch EMI photomultipliers showed an energy resolution around 8.2%. The modules with 3 inch Hamamatsu photomultipliers were not significantly better, which is a surprise because of their much larger active surface of the photomultiplier cathode and hence larger number of collected photons. Modules equipped with 1 inch Hamamatsu photomultipliers have systematically worse energy resolution by $\sim 3.5\%$ compared to the modules with 1.5 inch EMI.
photomultipliers, but further tests are needed to verify this fact. Worse resolution corresponds to our expectations in view of the smaller active surface of the cathode and thus smaller number of collected photons.

The modules equipped with 1 inch photomultipliers give also much smaller output pulse amplitudes than the 1.5 and 3 inch photomultipliers. When running at higher operating voltages to compensate the lower amplitudes saturation effects start to occur and the dynamic range is therefore limited.

### 6 Conclusion

The electromagnetic calorimeter ECAL is being developed to extend the experimental possibilities of the HADES setup up to the beam energies of 10 AGeV and hence to enable experiments on the newly build accelerator complex FAIR at Darmstadt, Germany. The calorimeter will provide measurements of diphoton pairs from meson decays and in combination with the charged particles reconstructed in the current HADES setup the calorimeter will also allow the measurements of ω production via the $\pi^0\pi^+\pi^-$ and the $\pi^0\pi^+\pi^-$ decays. Photon measurements are of large interest also for the strangeness program of the HADES experiment addressing mainly $\Lambda(1405)$ and $\Sigma(1385)$. Last but not least the calorimeter will contribute to enhancing the electron-pion separation at large momenta over 400 MeV/c.

The calorimeter performance was predicted using a set of simulations. The studied physics cases were modeled in the UrQMD and Pluto codes, events were subsequently analyzed in the GEANT 3 based HADES framework HGeant.

Calorimeter modules with various PMTs are being assembled and the energy resolution is being studied using LED light pulses introduced to the lead glass and cosmic muons triggered by a dedicated setup.

Two novel front-end boards based on separate time and amplitude measurement or charge to width conversion measurement are being developed. The general purpose TRB3 is foreseen as the digitizing board for the calorimeter. Beam test at MAMI-C facility in Mainz are planned for the near future to check the selected technical solutions.
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References


