ECFA Detector R&D Panel

CALICE Review Report

December 7, 2018

Members of the Review Committee:
Martin Aleksa, Silvia Dalla Torre, Doris Eckstein, Marek Idzik, Arno Straessner

Members of the ECFA Detector R&D Panel:
Phil Alport, Ariella Cattai (ex-officio), Silvia Dalla Torre, Doris Eckstein, Els Koffeman (Chair), Lucie Linssen, Laurent Serin, Arno Straessner

Date of review: November 6-7, 2018

Agenda of the review meeting:
https://indico.desy.de/indico/event/21353/

1 CALICE Status

1.1 Achievements since 2012 project review

The achievements of the CALICE Collaboration were last reviewed in 2012 by the ECFA Detector Panel. The recommendations derived by the Panel in this review were largely followed by CALICE. We would like to especially emphasize the following points: through the building and test of realistic detector layers and larger prototypes, the scalability of some proposed technologies, such as a semi-digital HCAL (SDHCAL), an analog HCAL (AHCAL) and a silicon-tungsten (SiW) ECAL, was validated. A large prototype of a scintillator-tungsten (ScW) ECAL is in preparation. Detailed comparisons between the data from beam tests with these prototypes and simulations were carried out and will be continued. A majority of the scientific results and technological advances was published or is in the pipeline for publication. It is remarked that the cooperation between the different activities and a concentration on the same DAQ and software optimized the usage of available resources.

1.2 Electromagnetic calorimeters and performance

At the time of the review in the year 2012, a physics prototype of the SiW electromagnetic calorimeter existed which was used during the test beam campaigns at DESY, CERN and FNAL in 2005-2011. Since then, the collected data have been analysed and an electromagnetic resolution parameterised by a stochastic term of 16.5 % and a 1 - 2 % constant term was obtained with a simple reconstruction algorithm. These results are in line with the requirements for a linear collider experiment, which aim in particular at particle-flow techniques for jet reconstruction, and agree with MC simulation. Pion and photon shower profiles were used to compare to GEANT4 simulations. During the last years strong effort was put into R&D aimed at establishing the feasibility of a large-scale SiW calorimeter, such as the design, production assembly and quality control of new front-end PCBs (FeV). These FeVs, including the first realistic long slab, were then tested in various test beams at CERN and DESY during the years 2015 - 2018. First analyses of this technological prototype with embedded electronics and larger channel density show the qualitatively expected results. Considerable effort went into system aspects such as carbon fibre reinforced carbon support structures or layout of services, as required by a linear-collider detector like ILD.

Two physics prototypes of a ScW electromagnetic calorimeter have been realised with external readout electronics which allowed demonstrating the viability of such a solution. An electromagnetic resolution parameterised by a stochastic term of 12.5 % and a 1.6 % constant term has been obtained in test beam measurements which were published in 2017. Work has started to realise a technological prototype with embedded electronics, reduced scintillator strip dimensions and direct read-out. Pixelated Geiger Mode silicon photo-detectors (SiPMs) with sufficient pixel density required for the dynamic range of the ECAL were obtained from Hamamatsu (MPPC). Different readout possibilities are being investigated which include side readout and bottom readout (SiPMs directly on the PCB). The goal is to construct and test a technological prototype in 2020. This prototype aims at applications at both linear and circular colliders.

1.3 Hadronic calorimeters and performance

The hadronic calorimeter technologies studied by the CALICE collaboration use tungsten and steel as absorber materials combined with different active layer technologies. In case of an analog readout, plastic scintillator tiles coupled to SiPMs are explored (AHCAL), while digital and semi-digital readout options (DHCAL and SDHCAL) are based on gas-filled RPCs, GEMs or Micromegas. In the past, physics prototypes for these options have been constructed and their performance in test beam has been measured.

Two prototypes of digital hadronic calorimeters with gaseous sensors have been realized and tested, both with pad-size of 1 cm^2 and steel absorber in layers of approximately 1 radiation length. The most advanced studies have been performed with glass RPCs as sensitive devices. In the DHCAL prototype, the digital electronics has a single threshold value, while in the SDHCAL prototype the information relative to three threshold values is registered. It is so possible to extend the dynamic range to the remarkable interval of 10 fC - 15 pC. Therefore, within the CALICE activity, SDHCAL emerges as the main technology for the digital approach to hadron calorimetry. A small-size SDHCAL prototype has also been successfully tested in magnetic field at 3 T. Measurements with a stronger magnetic field up to 4 T, also for larger setups, are still to be performed for all electromagnetic and hadronic calorimeter devices considered by CALICE.

Dedicated software tools have been developed for the data analysis of the SDHCAL. The single layer efficiency is $\sim$96%, with noise rate around 3 Hz/cm^2. Good response uniformity is obtained with a delicate equalization of the ASIC thresholds and gains. Efficiency and multiplicities are well reproduced in simulation exercises, after parameter tuning from electron and muon data. Dedicated studies using the ARBOR particle-flow algorithm (PFA) indicate a high separation power already after a calorimeter length of about 10 cm with good reconstruction efficiency and purity for reconstructed neutral particles. Layout studies and large-size glass RPC prototypes are preparing the way for a large-size prototype of total volume of 1 m^3. An upgrade of the technology to access fine-resolution time information is being considered: the approach would be via multigap RPCs and the use of the PETIROC ASIC, developed for tracking by RPCs in CMS. Furthermore, there is an ongoing research on replacing the RPC gas currently used (e.g. Tetrafluoroethane (TFE), SF_6) with eco-friendly alternatives. It is expected that higher RPC voltages will need to be applied (>10 kV).

A physics prototype of the AHCAL has been constructed in 2007, with readout electronics outside the absorber structure, and has been operated in several measurement campaigns since then. The AHCAL performance has been demonstrated in a combined test beam with a SiW ECAL and a tail-catcher, reaching a relative AHCAL energy resolution for single pions of $\sigma_E/E[\%] = (46.6 \pm 0.2)/\sqrt{E} \bigoplus (3.2 \pm 0.1)$ after software compensation, and $\sigma_E/E[\%] = (42.6 \pm 0.2)/\sqrt{E} \bigoplus (2.5 \pm 0.1)$ for the combined setup. Software compensation is a crucial element in energy reconstruction, improving the standalone performance of the AHCAL physics prototype by 23%, and the combined performance by 30%. A slightly worse energy resolution is observed for the SDHCAL technological prototype, where the semi-digital reconstruction also relies on hit and energy dependent weighting factors, similar to a software compensation.

The test beam results for an AHCAL with iron and tungsten show for both absorber types a linear behaviour of the energy response to pions and a similar sampling term in the energy resolution of $\approx 58\%$ (without software compensation). The constant term is measured to be $4.6\% \pm 0.4\%$ for tungsten, about three times larger than for iron ($1.6\% \pm 0.3\%$). However, non-contained showers in the test-beam setup influence these result and will be studied further with the recently constructed technological prototype.

The purely digital DHCAL suffers from saturation effects in particular at high hadron energies above 30 GeV leading to a non-linear response, which is due to a single amplitude threshold applied at hit level. This is largely improved, as already mentioned, with the 2-bit / 3-threshold scheme of the SDHCAL which provides sensitivity to the local particle density in each RPC cell. The development of the DHCAL technology is currently pursued with lower priority.

The construction of a large-size technological prototype of the scintillator-steel AHCAL with 38 layers has been completed recently. The layer thickness of absorber and sensitive detector are further optimized towards a linear-collider application. Like the SDHCAL prototype, it makes use of front-end electronics which is directly integrated in the detector structure and which can run in power-pulsed mode very similar to a future linear-collider operation.

The AHCAL technological prototype has been operated in test beam at CERN in summer 2018. The new prototype makes use of an optimized geometry of the scintillator tiles (wavelength-shifting fibers have been abandoned) and largely improved SiPM photo-detectors. The latter have a much reduced noise and dark count rate compared to those used in the physics prototype, as well as a very homogeneous behaviour across readout channels. In combination with a new SPIROC2E readout chip and a temperature-dependent HV regulation, an improved data quality and detector performance is expected allowing detailed 5D hadronic shower characterisation (position, energy, time).

1.4 Data comparisons to GEANT4 simulation

The behaviour of all CALICE prototypes is compared to GEANT4 simulations. This concerns not only the electromagnetic and hadronic energy resolution, but in particular the detailed longitudinal and lateral hadronic shower profiles including the time structure of the shower development. These analyses are of interest not only for the high-energy physics community but improves the understanding of hadronic interactions with matter in general.

When analysing CALICE data, reasonable agreement to GEANT4 simulations has been observed, with increasing deviations towards larger hadronic energies. Detailed track segment reconstruction, identification of the shower starting point, separation of showers into long/short and core/halo components are crucial in these analyses. Data currently indicate a preference for hadronic models like the Fritiof hadronic string model in combination with the Bertini intra-nuclear casade model (FTFP_BERT). To reach agreement with data, also the digitisation needs to be taken into account. In the AHCAL, the SiPM pixel number, noise, the finite integration time and the signal threshold are considered, while for the RPC detectors the avalanche formation for different particle densities and signal thresholds are important. Such effects degrade the ideal detector performance and thus need also to be propagated to full-detector concept studies for colliders.

Until today, nearly all CALICE studies of hadronic showers have been performed with a software framework that allows comparisons only up to GEANT4 version 10.1. Only the recent technological prototypes are being implemented in a new simulation framework that is now supported by the linear-collider community. This will allow comparisons to recent and upcoming GEANT4 releases (10.4 and beyond). This will ease the fast feedback between CALICE measurements and GEANT4 shower modelling, however at the cost of additional software development work. A continued simulation support is thus needed. The importance of the CALICE measurements which deliver unprecedented details of hadronic shower physics is well recognized by the GEANT4 team who is currently implementing the SiW ECAL test beam setup and the corresponding data as a benchmark scenario to which future GEANT4 releases will be compared to. An extension of this activity to CALICE test beam setups with technological prototypes would provide further handles in the development and verification of hadronic shower models. This is a crucial ingredient for the future application of particle-flow jet reconstruction.

1.5 Towards series and mass production

With the technological prototypes of the SiW ECAL, AHCAL and SDHCAL, the CALICE collaboration has explored and implemented detector construction techniques which aim at a future large-scale series production of detector elements. The design of detector components has been adapted to allow automated assembly techniques. At the scale of the large prototypes these were implemented successfully. Points of improvement, e.g. the mechanical stability of large-area PCBs or the transport of long detector slabs, have been identified. A close collaboration with industry and vendors has been established, e.g. for Si sensors and SiPMs, as well as for scintillator tiles which are produced in industry.

1.6 Electronics

A family of ASICs fulfilling the requirements of different calorimeter technologies was designed, fabricated, tested, and successfully proven in technological prototypes or multi-layer setups of different CALICE calorimeters. Most of the ASICs were designed in the AMS 0.35 μm SiGe process. The SKIROC chip is the core of the SiW ECAL readout, SPIROC is used for the scintillator readout of the AHCAL, HARDROC and MICROROC chips are used to read out the RPC and Micromega detectors of the SDHCAL. For the scintillator readout, the alternative KLAUS ASIC in UMC 180 nm CMOS process is also under development. The power pulsing feature was implemented in all ASICs as well as in complete readout systems of the calorimeter prototypes, and proven to work correctly in test beams. The next generation ASICs for CALICE test-beam application will in particular optimize self-trigger and zero-suppression techniques.

Recently, a new development of front-end electronics for the Si readout of the HGCAL in CMS has been started as a contribution to the CMS experiment. Modified version of the SKIROC chip for HGCAL test-beams and a first version of the HGROC chip for final readout of HGCAL have been developed in TSMC 130 nm technology. This development is particularly challenging but it will be also very profitable for the readout of future calorimeters since it is done in an advanced technology offering high speed and very low power consumption, together with very good radiation hardness. It is thus well adapted to the requirements of future HEP experiments. One should remember that most of the chips designed for CALICE calorimeters until today will not be used in a future linear-collider experiment, mainly due to limited lifetime of the technologies used in current designs. In this context, the experience gained in HGROC readout with an advanced TSMC 130 nm technology is invaluable for future technology transfer to CALICE ASICs. There are still some aspects of readout systems which need tuning or deeper exploration, before completing final designs for a linear-collider experiment. An example is the hit time measurement implemented in different ASICs. This feature has not been fully explored yet in the calorimeter's prototypes and a general question whether it is needed, and if so, at what precision, has not yet been fully answered.

For the demonstration of operation of different calorimeter prototypes a DAQ system was developed, with dedicated software components and hardware blocks addressing the interfaces to different calorimeter readouts. At highest level the DAQ is based on the EUDAQ framework. For each of the calorimeters a Detector InterFace (DIF) FPGA-based card and dedicated readout software were developed within CALICE. When needed, e.g. for the AHCAL prototype, an intermediate DAQ level, a Data Concentration block between the DIF and PC was developed, too. Proper operation and data taking during test-beams of different calorimeters have been proven and verified the common DAQ implementation.

2 CALICE Perspectives

The short-term perspective for the activity of the CALICE collaboration is very well defined. The collaboration has largely advanced in demonstrating the feasibility of high granularity calorimeters adequate for particle flow algorithms, by making use of different technologies. Nevertheless, this effort has to continue up to the completion of the program, which includes the analysis of all the data collected in test beam exercises using the different calorimeter prototypes, simulation studies where these data are exploited and further investigations also by additional test beam studies to bring the main proposed technologies to the same degree of maturity. The outcome of this completion of the current activities results in making the choice of the technologies for high granularity calorimetry fully educated and in improving the understanding of hadron interaction with matter, a field of wide interest in fundamental research, radioprotection and medical applications. Future CALICE test beam activities are moreover important to broaden the physics program by using different absorbers, e.g. tungsten with scintillator readout, and by exploiting the timing capabilities of the new prototypes.

The CALICE collaboration was established in view of the experiments at the ILC. Therefore, the most obvious evolution of the CALICE activity is in the linear-collider context, where the CALICE studies can be at the basis of the choices and the design of the calorimeter. The CALICE collaboration can also represent a kernel of the calorimeter group for the construction phase. At present, the uncertainty of the international scenario in matters of future colliders prevents this natural evolution.

The concept and goals of the high granularity calorimetry optimized for particle flow algorithms, make this approach particularly well suited for all applications requiring the accurate measurement of high energy hadron jets. This broadens the scope of the CALICE effort, as also recognized by the collaboration. The most obvious extension, already pursued, is for the use at CLIC. Looking further, another sector of application is at the circular electron-positron colliders, where the technologies require modifications to account for the unpulsed running mode of the accelerators. A third sector of application is at the high-luminosity LHC and, in fact, high granularity calorimetry is being realized for upgrades at CMS with the HGCAL and at ALICE with the FOCAL project. It has to be underlined that the development work by CALICE has largely contributed to the choice and the design of HGCAL. The CALICE collaboration is closely following these two projects, that represent an important experience in terms of performance in running experiments and of engineering for continuous powering. Applications beyond colliders can also be considered, as, for instance, at the DUNE near-detector.

3 Committee Recommendations

CALICE is a collaboration to develop, test and establish technological solutions for highly granular calorimeters optimised for particle flow, generally, but not exclusively, in view of applications at high energy lepton colliders. During the last years CALICE has demonstrated the feasibility of this concept by prototyping activities accompanied by simulation studies.

We recognize the effectiveness of the R&D collaborative effort and congratulate to the achievements realised in an environment where the internationally agreed path towards future high energy colliders is still open to different options.

Independent of this future development, the committee recommends that the CALICE collaboration continues to analyse the rich set of data that has been and will be collected in a number of test beam campaigns with prototypes of different technologies and to publish the results. These data are a crucial input for an improved understanding of hadronic showers. The exploitation of these data shall be continued in close collaboration with the GEANT4 team to contribute to an improved modelling of hadronic interactions, which is also of interest beyond high energy physics applications.

Furthermore, the CALICE collaboration is encouraged to bring the main proposed technologies to a comparable level of maturity and understanding, including a simulation of jet performance with particle flow algorithms. The collaboration is also invited to provide input for scalable cost models for the different technological approaches. This work will be the basis for the choice of an optimal calorimeter concept and layout in case of a positive decision about the realisation of a linear collider.

The CALICE studies established important ingredients for the decision and design of the CMS HGCAL, thus demonstrating the fertility of the CALICE effort. The HGCAL realisation offers the opportunity to validate the detector concepts in a full experiment and to profit from an advancement in integration aspects, mechanical engineering and development of electronics using technologies suited for future applications.

Since the calorimeter concepts studied by CALICE will be valuable for for particle physics experiments in general, including circular colliders, the CALICE collaboration shall be open for such applications. We encourage to explore the possibility of a un-pulsed, continuous operation of the calorimeters, which includes aspects of electronics readout, cooling and layout optimisation. The future CALICE test beam programme shall thus explore the timing capabilities of the new prototypes. Moreover, the physics programme may be extended by using further combinations of absorber and sensitive material, e.g. tungsten and scintillator.

A continued support in human and financial resources as well as access to and support at test beams is required to accomplish the goals according to the above mentioned recommendations.