Helmholtz-Hochschul-Nachwuchsgruppe VH-NG-206
"R&D studies for new photo-detectors and their integration in HEP detectors"

End of Project Report

Erika Garutti

The Young Investigator Group VH-NG-206 has started its activity on the 1st of March 2006 and has successfully concluded its five years duration at the end of February 2011. In this document I report on the group achievements of the entire period. The group has supported the work of three postdoctoral fellows, nine graduate students as well as five diploma students. A detailed list of the group members is given below. The list of the PhD and diploma thesis (concluded and in preparation) generated by the group is reported in the list of publications.

Group Members of the HGF Young Investigator Group

Group Leader:	Dr. Erika Garutti	DESY
Postdoctoral Fellow:	Dr. Martin Göttlich	DESY
Postdoctoral Fellow:	Dr. Shaojun Lu	DESY
Postdoctoral Fellow:	Dr. Niels Meyer	DESY
Graduate Students:	Nicola D'Ascenzo	DESY
	Sergey Morozov	DESY
	Nanda Wattimena	DESY

Associate Group Members from the partner institutes

University partners:	Prof. Dr. Rolf-Dieter Heuer	Univ. Hamburg
	J. Prof. Dr. Johannes Haller	Univ. Hamburg
	Prof. Dr. Hans-Christian Schultz-Coulon	Univ. Heidelberg
	Prof. Dr. Tohru Takeshita	Univ. Shinshu
Graduate Students:	Nils Feege	Univ. Hamburg
	Marius Groll	Univ. Hamburg
	Alexander Kaplan	Univ. Heidelberg
	Wei Shen	Univ. Heidelberg
	Alexander Tadday	Univ. Heidelberg
	Saori Ito	Univ. Shinshu
Diploma Students:	Alexandra Eggemann	Univ. Lubeck
	Nils Feege	Univ. Hamburg
	Niklas Hegemann	Univ. Hamburg
	Sebastian Richter	Univ. Hamburg
	Maximilian Schmidt	Univ. Hamburg
	Susanne Jungmann	Univ. Heidelberg

Main commitments and achievements of the group

The CALICE hadronic calorimeter prototype (AHCAL)

The group is member of the CALICE (Calorimeter for a Linear Collider Experiment) collaboration, a broadly international collaboration of 336 physicists/engineers from 57 institutes and 17 countries coming from the 4 regions (Africa, America, Asia and Europe). The main objective of CALICE is the development of the next generation of calorimeters for future HEP detectors, based on innovative technologies to allow unprecedented granularity and segmentation of all detector components.
Among the detectors investigated by the collaboration, a highly granular hadronic calorimeter prototype (AHCAL) has been developed based on a sampling structure with scintillating tiles (of smallest size $3\times3\times0.5$ mm^3) individually readout by innovative silicon-based photo-detectors (Silicon-Photomultiplier (SiPM), from MEPHY/ PULSAR) mounted directly on each tile. Due to the green sensitivity of the photo-detector a wavelength shifting fiber is used to couple the scintillation light to the SiPM.
After the very first commissioning run in 2006, the fully equipped calorimeter prototype was tested at CERN and FermiLab test beams with approximately two data taking periods per year. Tests are still ongoing with the same prototype at CERN this year where the absorber structure of the calorimeter has been changed from steel to tungsten.

The operation of the detector, mainly driven by the photo-detectors, has been stable and the collaboration has gained a large experience in calibrating and monitoring a calorimeter with about 8000 channels.

The analysis of the physics data collected in all the years is still in full swing. Many results are reported already in the CALICE publications to which the HGF group has significantly contributed.
During the years of test beam experiments the group has taken a leading role in several aspects of the commissioning, operation, software development and analysis of the AHCAL. The roles of CALICE test beam coordinator (E. Garutti), CALICE software coordinator (N. Meyer, S. Lu) as well as analysis coordinator for the DESY group (E. Garutti) have been covered by members of the HGF group. A large contribution to shifts was provided as well as on-call experts (M. Groll, A. Kaplan, N. Feege) during the installation, commissioning and running phase.

After the end of the HGF group the continuation of the activities in the frame of CALICE is ensured for all group members via the individual contracts with the hosting institutes, but additional third party funds are needed to maintain the level of contribution which has been possible thanks to HGF. This year a new EU-funded FP7 project (AIDA) has started, which will partially support the development of the next generation hadronic calorimeter prototype.

Remote control room for ILC test experiments

In year 2008 the group has received an extra grant from HGF (Sonderförderung SO-NG-064). Thanks to this it was possible to make a significant contribution to the realization of a remote control room, located at DESY, for the control of the ILC test beam activities around the world. The control room ensures the capability to run the experiment remotely with the help of highly sophisticated tools like high-resolution steerable cameras and a web-accessible oscilloscope. The easy exchange of information with the local crew in FermiLab is ensured by a high quality audio conferencing system, which acts as an open window between the two control rooms.

The operation started in time for the first test beam in FermiLab in year 2008, and has significantly improved the communication and support of shift crews and experts to the experiment in Chicago. In years 2011 and 2012 the control room will continue its operation connected to the ongoing test beam at CERN.

Research and study of new photo-detectors

During its mandate the group has intensified the laboratory activities of tests of new photo-detectors and their application to new fields. Various applications have been tested like readout of Cerenkov light from crystals and specific detection methods for medical applications.
For this purpose the group has gained vast expertise in characterizing SiPM devices. Several test-setups at the the University of Heidelberg and at DESY have been developed. With these tools it is possible to perform measurements of the gain and dark-rate of SiPMs, as well as the cross-talk and after-pulse probabilities as a function of the bias voltage and temperature. Further it is possible to raster-scan the SiPM surface with a focused light spot which allows to determine sensitivity, gain and cross-talk probability depending on the geometrical position illumination. Focus has been set on the measurement of the cross-talk and after-pules corrected photon detection efficiency (PDE) as these effects would, if not taken into account properly, overestimate the PDE values. A combination of the measurement results allows to determine the individual noise contribution to the photon counting resolution of SiPMs and to define an application specific optimal operating voltage.
Photodetectors from the main producers on the market have been characterized and compared, including the photo-detectors used already in the AHCAL.

These test stands have been further supported and extended via the HGF "Alliance at the Terascale" project and have become part of the "Virtual SiPM Laboratory", a national organization aimed to strengthen the existing research efforts on SiPMs and gain from an intensified collaboration between the participating institutes.

The infrastructures of the Virtual SiPM Laboratory are currently in use for another round of products comparison in view of the selection of the photo-detector for a EU-funded FP7 medical project (ENDO TOFPET US).

Development of a detector for Positron Emission Tomography

The main challenges posed by the design of future Positron Emission Tomography machines are the improvement of the spatial and timing resolution and the combined operation with magnetic resonance. The Micro Pixel Photon Counter by Hamamatsu is a good candidate for this application. Its small size (down to 1×1 mm^2) and the high photo-detection efficiency in the blue spectral region allow the direct readout of a highly segmented scintillator matrix improving the spatial resolution of the machine. Furthermore, this photo-detector is insensitive to static magnetic fields up to 5 T, which makes it a possible candidate for applications in a magnetic resonance environment. The design of a PET prototype detector with SiPM readout was developed. Through the HGF Sonderförderung SO-NG-064 100 LFS crystals and the photo-detector needed for the PET detector readout have been financed, and characterization tests have been performed in the set-ups described above.
The Heidelberg group has developed an ad-hoc designed chip for PET application. Tests of the first submission of the chip were very encouraging and a second submission is ongoing. The Heidelberg group has also contributed with engineering support, providing

the mechanical structure and the motor-driven rotation system for the detector.
The PET prototype has been built and operated since year 2009 with a preliminary read-out system, while waiting for the final chip designed by Heidelberg. The achieved coincidence time resolution amounts to 870 ps FWHM, and is limited by the sampling rate of the readout electronics. We demonstrated that with a relatively simple approach a very good performance in terms of spatial resolution (2.5 mm FWHM) can be achieved. In addition, we showed that we can reach a very good channel-to-channel homogeneity and stability of the system by monitoring the temperature and adjusting the MPPC bias voltages individually. The well-understood test device allows us to test new developments for the multi-channel read-out of MPPC devices. This gives us the possibility to experimentally investigate the improvement of the image quality using TOF information. Results of the characterization of the PET prototype detector and of the first image reconstruction measurements are reported in our publications. Measurements are still ongoing which will be the topic of the last diploma thesis (M. Schmidt) using this device and the subject of another publication.

Thanks to the experience gained within this part of the project a proposal to the EU funded FP7 medical program was submitted and a new project (ENDO TOFPET US) has been funded, which started in Jan. 2011. The project will include the design and development of an endoscopic PET detector to study biomarkers for prostatic and pancreatic cancer. The design of one part of the next PET detector is largely based on the prototype PET detector developed by the HGF Young Investigator Group. I will personally be the leader of the integration work package of this FP7 project.

Conclusions and Acknowledgments

As concluding remarks I would like to point out that via the HGF Young Investigator Group VH-NG-206 I have been able to significantly support and improve the activities of the DESY group in the frame of CALICE; I have established a strong link to the universities of Heidelberg, Hamburg and Shinshu especially in the test, characterization and application of SiPMs; I have started a fully new activity at DESY in the field of applied detector physics in particular for Positron Emission Tomography.
These five years have been extremely fruitful for me and for my group as it can be seen from the amount of publications produced, but also from the new third party funds acquired to continue the projects in which the group is involved. Finally, the visibility, the level of responsibility and the experience which I personally gained during these years have opened the possibility for my next career step as an associate professor at the University of Hamburg. For all these many opportunities and for the excellent support I am extremely grateful to HGF.

List of Publications

1. N. D'Ascenzo, E. Garutti, M. Groll, ..., N. Wattimena, et al. *CALICE scintillator HCAL commissioning experience and test beam program*, LC-DET-2006-009.

2. E. Garutti, M. Groll, et al. *Dedicated very front-end electronics for an ILC prototype hadronic calorimeter with SiPM readout*, LC-DET-2006-007.

3. E. Garutti *CALICE scintillator HCAL commissioning experience and test beam program*, Proceeding to the conference CALOR'06, Chicago, 5-9 Jun 2006.

4. N. Meyer et al. *Production and Detection of Assion-like particles in a HERA dipole magnet*, Letter of Intent for the ALPS experiment, DESY-07-014, hep-ex/0702023.

5. M. Groll. *Construction and commissioning of a hadronic test-beam calorimeter to validate the particle-flow concept at the ILC*, Universitt Hamburg DESY Thesis (2007), DESY, Hamburg DESY-THESIS-2007-018.

6. A. Eggemann. *Messungen zur Anwendung von Geiger Mode Photodioden*, Diploma thesis, 2007.

7. N. D'Ascenzo, A. Eggemann, E. Garutti. *Study of Micro Pixel Photon Counters for a High Granularity Scintillator-Based Hadron Calorimeter*, DESY internal note DESY07-196, and arxiv-ph/0711.1287.

8. N. D'Ascenzo, A. Eggemann, E. Garutti, A. Tadday. *Application of Micro Pixel Photon Counter to calorimetry and PET.* Proceeding to the Workshop on Photon Detection, 13-14 June 2007, Perugia, Italy.

9. N. D'Ascenzo, E. Garutti, A. Tadday. *Application of MPPC to positron emission tomography.* PD07 conference proceeding, May 2007, Kobe, Japan.

10. E. Garutti, N. D'Ascenzo, M. Göttlich, H.-C. Schultz-Coulon, A. Tadday. *Application of novel Silicon-based photo-detector to calorimetry and medical physics.* IEEE conference proceeding, 31 Oct - 3 Nov 2007, Honolulu, Hawaii.

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13. N. D'Ascenzo, E. Garutti, M. Goettlich, H.C. Schultz-Coulon, A. Tadday. *Study of Micro Pixel Photon Counter for the Application to Positron Emission Tomography*, DESY-08-047, May 2008., e-Print: arXiv:0805.0525.

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15. E. Garutti, M. Goettlich, H.C. Schultz-Coulon, A. Tadday, et al. *Application of Multi-Pixel Photon Counter to Positron Emission Tomography*, Proceeding to the IEEE08 conference, 19-25 October 2008, Dresden (Germany).

16. N. Feege *Silicon Photomultipliers: properties and application in a highly granular calorimeter* , Diploma thesis, 2008.

17. S. Richter *Validation of the calibration procedure for a highly granular calorimeter with electro-magnetic processes.* , Diploma thesis, 2008.

18. A. Tadday *Characterisation of Silicon Photomultipliers.* , Diploma thesis, 2008.

19. N. Meyer *Muon, electrons and hadrons in the CALICE tile hadron calorimeter prototype.* , Poster presented at the ICHEP conference, 2008, Philadelpia.

20. N. Wattimena *The CALICE tile hadron calorimeter prototype with SiPM readout: design, construction and first test beam results.* , Proceeding to the Astroparticle, Particle and Space Physics, Detectors and Medical Physics Applications conference, 2008, Como, Italy.

21. C. Adloff et al.
Response of the CALICE Si-W electromagnetic calorimeter physics prototype to electrons.
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24. Nicola D'Ascenzo, *"Study of the Neutralino Sector and Analysis of the Muon Resoponse of a Highly Granular Hadron Calorimeter at the International Linear Collider"*,
Universitt Hamburg DESY Thesis (2009) DESY-THESIS-2009-004.

25. Patrick Eckert,Hans-Christian Schultz-Coulon, Wei Shen, Rainer Stamen, Alexander Tadday*,
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26. P. Jarron, E. Auffray, S.E. Brunner, M. Despeisse, E. Garutti, M. Göttlich, H. Hillemanns, P. Lecoq, T. Meyer, F. Powolny, W. Shen, H.C. Schultz-Coulon, M.C.S. Williams *Time based readout of a silicon photomultiplier (SiPM) for Time Of Flight Positron Emission Tomography (TOF-PET)*, Symposium IEEE 2009, October 2009, Orlando, USA.

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29. Martin Göttlich*, Erika Garutti, Alexander Tadday, Hans-Christian Schultz-Coulon *"Application of Silicon Photomultipliers to calorimetry and to Positron Emission Tomography"*, proceeding PD09 workshop on new photodetectors, PoS(PD09)009

30. Wei Shen, Hans-Christian Schultz-Coulon, *"STIC: A Current Mode Constant Fraction Discriminator for Positron Emission Tomography using SiPMs (MPPC)"*, proceeding IEEE-NSS 2009, Orlando, USA, 2009.

31. N. Wattimena, *Calorimetry at the International Linear Collider - From Simulation to Reality*, Universitt Hamburg DESY Thesis (2010), DESY, Hamburg DESY-THESIS-2010-006

32. The CALICE Collaboration (C. Adloff et al.).
CALICE Report to the DESY Physics Research Committee, arXiv E-Print (only) (2010), PRC 2010; arXiv:1003.1394, http://arxiv.org/abs/arXiv:1003.1394.

33. The CALICE Collaboration (C. Adloff et al.).
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34. The CALICE Collaboration (C. Adloff et al.).
Electromagnetic response of a highly granular hadronic calorimeter, Red Report (2010) DESY 10-241 http://arxiv.org/abs/arXiv:1012.4343

35. The CALICE Collaboration (C. Adloff et al.).
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