Final Report

Funding Programme:	**Helmholtz Joint Research Groups**
Project ID No.:	HCJRG-300
Project Title:	Novel Technologies for the Upcoming Silicon Micro-Strip Detector of the ATLAS Experiment at CERN
Principal Investigator:	Dr. Ingrid-Maria Gregor, DESY

1) Work and Results Report

Please describe the main results and the progress achieved through the Joint Research Group in comparison to the state of the art at the time of writing the application and give an outlook on possible future work and applications.

a) Description of the results (max. 4 DIN A4 pages)

Please describe the scientific and/or technical success of the group as well as secondary results achieved and essential experience gained

The programme of the research group HCJRG-300 addressed several vital performance issues for silicon strip modules to be operated within the ATLAS experiment in the harsh environment of the high luminosity LHC (HL-LHC) at CERN. The work was organised in three work packages covering the module performance before and after irradiation, the thermal effects and the powering scheme of the silicon strip modules. Various prototypes of stand-alone modules as well as more complete structures like a petalet were constructed and tested.

Figure 1: Fully functional ATLAS ITk Strip module prototypes, also used to evaluate powering options.

In the following a "sensor" is the active element based on a silicon pn-junction which can detect charge particles if it is operated with a reverse bias voltage. A "hybrid" is a light flexible electronics board containing the front-end chips and passive electronics to convert the signal charge from the sensor into a digital hit/no-hit information. A "module" consists of a silicon sensor with the hybrid directly glued onto the surface of the silicon sensor. In Figure 1 three fully functional module prototypes as constructed within this project are shown.

WP1: Silicon micro-strip detector performance before and after irradiation

In the course of the project prototype silicon sensors with embedded fan-ins in a second metal layer were design in cooperation with CNM Barcelona in Spain to investigate the effect of such fan-ins on the module performance. Such embedded fan-ins enable us to different geometries and potentially simplify the module construction. The modules with the embedded fan-in sensors were studied in detail at a test beam and the results of the study were fed back into the module design. Based on these studies it was decided not to use such embedded fan-ins for the ATLAS experiment as the embedded fan-ins introduced inhomogeneous noise which is difficult to subtract in a real experiment. Studies of the bond pad regions on silicon strip sensors have confirmed that the effective width of the strip is larger at the location of the bond pads. It was found that the strip response can be attributed mainly to the geometry of bond pads, with the impact of isolation implementation positions (p-stop) being much smaller.

In a study of silicon strips sensors at the DIAMOND light source at RAL in the UK, it was observed that the implantation structures (p-stop) at the surface of the sensor to define the insulation between strips is influencing the charge collection at the location of the p-stop. The glue to attach the hybrid onto the sensor influences both the charge collection and the signal clustering. These results had a direct impact on the design of the final silicon strip sensor to be used within the ATLAS experiment and will also have an impact on the module design of future experiments. In this context. it was also observed that irradiation is curing the adhesive underneath the chips which is ensuring the stability of the silicon modules.

A significant study within this HCJRG was the choice of the glues to attach the front-end chips onto the hybrid. The selected glue not only has to meet strict specifications on electrical conduction, mechanical strain and viscosity, but also has to meet the same specifications after being irradiated to levels comparable to irradiation levels at the end-of-lifetime of the experiment. Seven glues were investigated as possible alternatives to the silver epoxy glue originally used, most of them were UV curable glues with the goal to also optimise the time needed for this production step. All glues were tested and found to be suitable for the construction of hybrids and to provide sufficient thermal conduction between the components. Thermal tests have been conducted for the three preferential UV cure glues and no significant difference has been found in the thermal behaviour of hybrids glued with silver epoxy glue or UV cure glue. First hybrids, glued with UV cure glues, showed electrical performances comparable to a hybrid glued with a silver epoxy glue.
In a next step module prototypes were constructed by using hybrids with a UV glue. Based on this detail study it was decided within the ATLAS collaboration to use the chosen UV glue as baseline glue for all the 20000 modules to be produced for the HL-LHC ATLAS strip detector.

A major achievement was the study of a fully functional module before and after irradiation with a radiation level comparable to the level to be expected at the end of the high-luminosity phase of the LHC. In this study, it could be shown that the module will still be fully functional towards the end-of-lifetime. These studies were conducted using a pixel telescope maintained by members of this research group. Also, main aspects of the necessary data analysis were conducted by members of the team. The results were published prominently in the Technical Design Report for the Upgraded ATLAS Strip Detector.

In addition, a method was developed to measure precisely the radiation length of an object and prepare detailed maps of the radiation length for complex structures like the modules. The method is referred to as X0 measurement in the following.

WP2: Thermal effects
To enable the evaluation of thermal effects on a realistic ATLAS ITk strips endcap detector module, thermo-mechanically viable and realistic models had to be designed and constructed, as no fully realistic modules existed at the time of the start of the study. For that purpose, dedicated readout and powering structures were designed and built, as well as

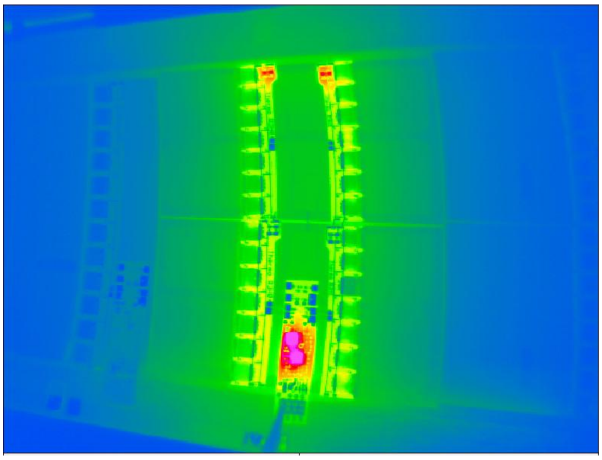

Figure 2: Infrared image of thermo-mechanical

equipped with dummy ASICs with embedded heating elements corresponding to the expected heat load of the future ATLAS ITk strip readout ASIC. Additionally, silicon sensor models were constructed by laser-cutting the complex endcap wedge sensor shape with rounded edges from plain silicon wafers.

These building blocks were then assembled into module models using the default ATLAS ITk Strips adhesives. A full set of two times thirteen different modules types were built and subsequently assembled onto a realistic carbon fibre support structure with all the planned future components. This full petal model allowed the study of the thermo-mechanical behaviour in a realistic setup. To measure temperatures dynamically and with very high spatial resolution a dedicated setup was established and calibrated. A "show and tell" picture of one of the first "modules-on-core" being powered up and observed with that setup is shown in Fig. 2. The key result of these measurements is the ongoing comparison and subsequent refinement of the thermal simulation of the future detector. Agreements between the measurements and the simulation at the level of about 10% could already be obtained. Future studies can include the evaluation of irradiated thermal models or models constructed with alternate materials, should the need for alternate materials arise.

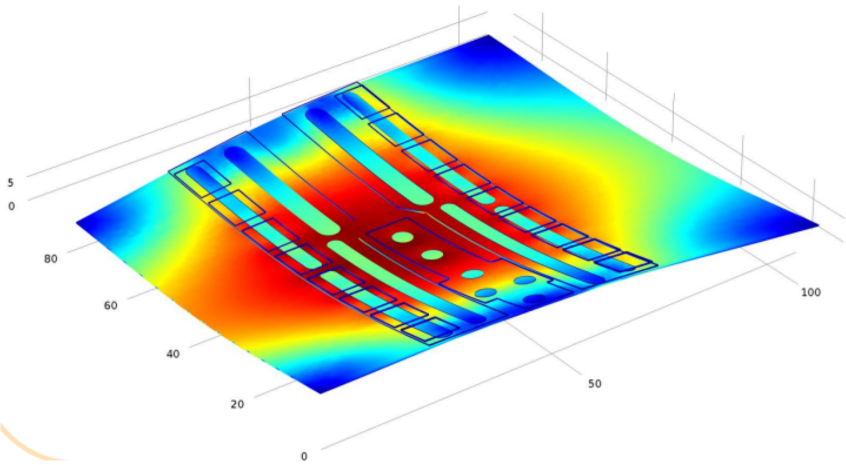

Figure 3: Simulation of the deformation of an endcap strip detector module.

Initial studies quickly showed that the mechanical stress which the readout structures (with a coefficient of thermal expansion different from that of silicon) transfer to the silicon sensor due to differences in temperatures during detector construction (20°C) and operation (-35°C) had to be understood in more detail to prove that the sensors would still perform as required after 10 years of HL-LHC operation and in the very severed irradiation field of the HL-LHC (~60 MRad and 1.6e15 neq/cm^2). For this, very detailed simulations were performed and compared in detail with results from thermo-mechanical module-models constructed at elevated temperatures. The result of a simulation run for a given module type is shown in Fig 3. These results are compared at micrometre level with realistic mechanical modules to validate the simulation. Effects of the impact of such levels of mechanical stress on the sensor performance have been evaluated in test beam measurements and in the beta-setup. The analysis of these measurements is still ongoing but initial findings indicate that the modules will perform within the specified requirements throughout their full ten-year HL-LHC operation. Further studies, aging mechanical modules in thermal cycles in a climate chamber, emulating the ten-year experience, also indicate the appropriateness of the ITk strips module design.

WP3: Powering decision

Early-on during this project, the ATLAS ITk Strips community decided to pick DCDC powering over the alternative of serial powering. This decision allowed a dedicated focus on the evaluation of electrical, thermal and mechanical performance and radiation hardness of the DCDC powering scheme. The power-board placement, which originally was planned not to be part of the strip module, was moved onto the silicon sensor, following the example of the readout structures that had already been foreseen for this concept. Examples of the endcap power-board structure designs that were developed, built and evaluated with support and collaboration from this project are shown in Fig. 4. These developments and studies are led by our collaborators from the Humboldt University of Berlin. Several smaller design flaws leading to higher module electronic noise could be identified and fixed during those studies. A rich set of new features for the powering options was enabled and full module functionality could be demonstrated. Several components of the power-board, among them the final DCDC-converter ASIC, are not yet available in their final version, so e.g. the performance after irradiation remains to be proven. However, several sub-steps have already demonstrated sufficient radiation hardness for use in the HL-LHC strip tracker. The thermo-mechanical model of the petal (see WP2) also included realistic power-boards which showed that, using the intended materials, also this behaviour will be within required detector performance parameters.

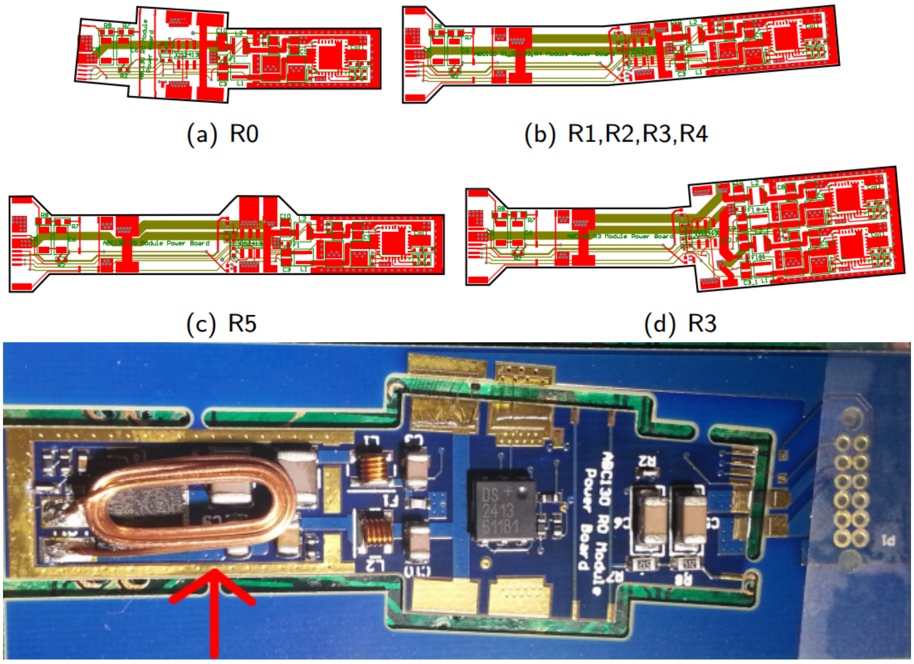

Figure 4: Power-board designs and an initial prototype. These power-boards transform the 11V delivered on the lower lines to the module voltage level of 1.5V

b) Outlook on future work, sustainability (max. 2 DIN A4 pages)

How far did the JRG intensify the scientific cooperation between Helmholtz and international partners? Did it set new impulses in existing and upcoming research programmes of the Helmholtz Association? Does it form the core of a future, larger scale bilateral or otherwise funded project? Please describe planned activities/ cooperations to further develop the work, if applicable also with additional partners.

The HCJRG-300 was extremely helpful for the cooperation between the Chinese colleagues at IHEP and the team at DESY. The collaboration with Hongbo Zhu and his team strengthened and consolidated an intense relationship of trust. The awareness of the work and progress of both teams intensified. As a consequence, more colleagues from IHEP are applying for DESY positions and vice versa. In addition, more highly qualified young scientists are taking part in combined programmes, for example the Germany-China Helmholtz-OCPC postdocs program. By now both teams at DESY and IHEP are established major players in the ATLAS ITk community and approved module production sites. Further combined projects centred around the ATLAS ITk strip detector or upcoming future projects are envisaged.
In addition to the intensified collaboration between IHEP and DESY, the project helped to reach out to further international partners. The teams are working closer with the team from the

Liverpool University to exchange expertise on composite materials and glues. Through the special sensor designs, a close collaboration between CNM Barcelona was established and will be continued in the future.
Important to mention is the dissemination of knowledge through the junior researchers which were involved in the HCJRG-300. All junior researcher which left DESY in the meantime were accepted by renowned institutes for their next step in their career. Thus, spirit and the knowledge acquired in the project is disseminated within the community.

c) Potential for application/exploitation (max. 2 DIN A4 pages)
How do you yourself assess the potential for application or exploitation of the results? Where do you see future possibilities? Please describe realized or planned measures for applying the results. Please also include information on patents, licences, co-operations with industry, etc.

Most, if not all of the results obtained from the studies performed in the context of the JRG have a direct application or consequence in the context of the ATLAS central tacking detector upgrade for the HL-LHC phase. Many of the findings allow for faster future detector developments and for design of detectors with reduced material.

- The adhesive evaluations (see WP1) allowed ATLAS to pick one of the evaluated adhesives as the new default for ASIC connections in the strip detector. The qualification of the adhesive will furthermore allow the application of these adhesives in future detectors with comparable harsh radiation environments. An example where this has already been applied is the beam radiation monitor of the CMS experiment
- The thermal and mechanical evaluations proved that the module design is a valid choice for the boundary conditions given by ATLAS and the HL-LHC
- The power-board could be prototyped and improved, allowing its use in ATLAS
- The X0 measurements make it possible to feedback very precise material maps into the global simulation of ATLAS and thus enable reduced systematic uncertainties in future ATLAS measurements as well as being available as a powerful tool for any future detector development that requires precise knowledge of the material distribution
- The alternative sensor options that were evaluated are important to understand effects observed in similar sensor architectures and will allow to use this very material efficient method in future HEP detectors
- The observation of adhesive fluorescence and subsequent increase of signal in the silicon detector opens the door for future signal enhancement strategies

2) Qualification of Junior Researchers (max. 2 DIN A4 pages)
Please describe the main achievements regarding personal qualifications (Diploma, bachelors or masters degrees, conferring of doctorates, “habilitations”, appointments/junior professorships, etc.). How far have new career perspectives for young scientists inside the foreign country been developed?

During the course of the programme a number of young scientists worked on various aspects of the project. Only a few were directly supported by the HCJRG grant while others were financed through DESY. All of them were using equipment and material. In the following all junior researchers are listed with a short list of their achievements and the new career perspectives.

Luise Poley: PhD student throughout the project and co-funded by HCJRG. She focused on adhesive choices and effects of adhesives on silicon sensor properties. Her research and presentations thereof led to her being considered one of the central experts in terms of adhesives interacting with silicon within ATLAS and beyond. She recently defended her PhD thesis successfully at the Humboldt university in Berlin and was accepted for the prestigious Chamberlain Fellow at the Lawrence Berkeley Laboratory in Berkeley, California.

Martin Stegler: PhD fully funded by HCJRG, exploring very new area of mechanical stress on sensor surface (adhesive connection to readout). He is ecoming recognised as expert for impact of deformations and stress on silicon behaviour. He received the award for the best poster at the Hiroshima conference.

Marko Milovanovic: PostDoc throughout the project and co-funded (50%) by HCJRG. He focused on very compact cooling and support structures for silicon sensor and module evaluation in test beams and beta-source setups.

Dennis Sperlich: PhD student fully funded by our partner Humboldt university. His main objective was the development of the ATLAS strip tracker module power board. The research conducted by him was heavily supported by HCJRG funding in cooperation with Chinese colleagues (Yi Liu, testbeam, see below). Dennis is currently finishing his PhD thesis and already received an offer for postdoctoral position at the Freiburg University.

Richard Peschke: PhD student; focussing on the preparation and conduction of the test beam studies of full silicon strip modules. He adapted the analysis software to synchronise the strip module data stream with the telescope data stream. He defended his PhD successfully and is now accepted as postdoc fellow at the University of Hawaii.

Edoardo Rossi: PhD student; test beam - irradiated module (telescope). Strongly involved in study of irradiated sensors and modules. Leading the test beam activities and the analyses of the data.

Jan-Hendrik Arling: PhD student - test beam (radiation length measurement) and thermal measurements of thermo-mechanical prototype.

Yi Liu: postdoctoral researcher within the Germany-China Helmholtz-OCPC postdocs program. His work was mostly focussed on the data acquisition system to read out the full data from the modules. By now he is accepted as DESY fellow.

Xiaocong Ai: postdoctoral researcher within the Germany-China Helmholtz-OCPC postdocs program. Her work was mostly focussed on the data analysis of the test beam data and general tracking software.

Nataliia Zakharchuk: PhD student working on electrical and mechanical tests of the full petalet. Now accepted as postdoc at the Carleton University in Toronto, Canada.

Laura Rehnisch: Former PhD and now postdoc at Humboldt University Berlin. Strongly involved in test beam studies and data analysis.

Kristin Lohwasser: Former postdoc; supervision of PhD students around the test beam analyses. Setup of the beta measurement tool. By now research fellow at the Sheffield University with an ERC grant.

Claire David: Postdoc supervising PhD students around thermo-mechanical measurements.

3) Public relations
By which means did you gain publicity (e.g. reporting in media, own website)?

The team was also active in public relations, but to a lesser extent. The main activity here were presentations at conferences

- 5 poster contributions with results at 11th Hiroshima symposium (see publication list, and https://indico.cern.ch/event/577879/)
- Luise Poley, presentation at the IEEE NSS 2016 in Strasbourg, France
- Jan-Hendrik Poster at the Forum on Mechanics 2017 in Marseille

One generic outreach movie for high energy physics with strong focus on international collaboration: https://www.youtube.com/watch?v=Fsk2CPNHkwU

4) Networking
What co-operation and communication structures have been developed during the course of the funding? What is the contribution of the group to the networking of international partners and the Helmholtz Centre(s)?

A number of additional co-operations were developed during the course of the funding. In the following a few are listed including the contribution by the partner:

- Karlsruhe Institute of Technology (KIT) and University of Ljubljana irradiated sensor and module samples to HL-LHC levels
- CH company providing additional information on the used glues
- CNM Barcelona developed sensor prototypes with embedded fan-ins and other modification proposed by the HCJRG
- DIAMOND light source at RAL, UK (e.g. fluorescence of adhesive on sensor surface)
- Chinese colleagues at DESY as guest researchers (see below)
- CMS Collaboration at CERN: exchange of information about glue studies
- Belle collaboration: material studies in the test beam
- Expert user of the DESY II Test Beam Facility and enabled the use of this facility to many other users from ATLAS

5) List of Publications
Articles in scientific journals, written contributions to scientific meetings, contributions to books, other publications.

1. Prototyping of petalets for the Phase-II Upgrade of the silicon strip tracking detector of the ATLAS Experiment
   S. Kuehn (CERN) et al.. Nov 5, 2017. 22 pp.
   Published in JINST 13 (2018) no.03, T03004

2. Investigations into the impact of locally modified sensor architectures on the detection efficiency of silicon micro-strip sensors
   Luise Poley (DESY) et al.. Nov 18, 2016.
   Published in JINST 12 (2017) no.07, P07006

3. Embedded pitch adapters: A high-yield interconnection solution for strip sensors
   M. Ullán (Barcelona, Inst. Microelectron.) et al.. 2016. 8 pp.
   Published in Nucl.Instrum.Meth. A831 (2016) 221-228

4. Evaluation of the performance of irradiated silicon strip sensors for the forward detector of the ATLAS Inner Tracker Upgrade
   R. Mori (Freiburg U.) et al.. 2016. 6 pp.
   Published in Nucl.Instrum.Meth. A831 (2016) 207-212

5. Sensors for the End-cap prototype of the Inner Tracker in the ATLAS Detector Upgrade
   V. Benítez (Barcelona, Inst. Microelectron.) et al.. 2016. 7 pp.
   Published in Nucl.Instrum.Meth. A833 (2016) 226-232

6. Enabling Technologies for Silicon Microstrip Tracking Detectors at the HL-LHC
   C. Barth (KIT, Karlsruhe, EKP) et al.. Apr 28, 2016. 47 pp.
   DESY-16-072

7. Characterisation of strip silicon detectors for the ATLAS Phase-II Upgrade with a micro-focused X-ray beam
   Luise Poley (DESY) et al.. Mar 15, 2016. 17 pp.
   Published in JINST 11 (2016) no.07, P07023

8. Alternative glues for the production of ATLAS silicon strip modules for the Phase-II upgrade of the ATLAS Inner Detector
   Luise Poley (DESY & Humboldt U., Berlin) et al.. Aug 24, 2015. 23 pp.
   Published in JINST 11 (2016) no.05, P05017

9. Technical Design Report for the ATLAS Inner Tracker Strip Detector
   ATLAS Collaboration. Apr 1, 2017.
   CERN-LHCC-2017-005, ATLAS-TDR-025

10. Studies of adhesives and metal contacts on silicon strip sensors for the ATLAS Inner Tracker
    Luise Poley (DESY & Humboldt U., Berlin)
    PhD Thesis, Humboldt University

11. Posters at Hiroshima Conference:
    a. L. Poley - Studying signal collection in the punch-through protection area of a silicon micro-strip sensor using a micro-focused X-ray beam:
       Summary: https://indico.cern.ch/event/577879/contributions/2740109/
    b. M. Stegler - Investigation of the impact of mechanical stress on the properties of silicon strip sensors:
       Summary: https://indico.cern.ch/event/577879/contributions/2740110/
    c. D. Sperlich - Signals from fluorescent materials on the surface of silicon micro-strip sensors:
       Summary: https://indico.cern.ch/event/577879/contributions/2740111/
    d. L. Rehnisch - Testbeam results on pick-up in sensors with embedded pitch adapters:
       Summary: https://indico.cern.ch/event/577879/contributions/2740114/
    e. L. Poley - Study of n-on-p sensors breakdown in presence of dielectrics placed on top surface:
       Summary: https://indico.cern.ch/event/577879/contributions/2740138/