

## International Big Science: IBS serves CERN and Partner Institutes Worldwide

**Successful commissioning of sensor module assembly machines for ALICE detector upgrade.**



The ALICE detector, part of CERN's flagship of groundbreaking nuclear research, the Large Hadron Collider, is due for an upgrade in 2019-2020. The specified improvement of spatial resolution, tracking efficiency and read-out rate capabilities puts highest demands on the assembly of the sensor modules. IBS Precision Engineering won contracts with CERN and partner institutes worldwide for the development and construction of a sensor module assembly machine, called ALICIA. A total of seven machines were commissioned within a tight time schedule, and the eighth one is due for end of this year. Key success factors of the ALICIA development project were system integration, multicultural communication and flexibility.

IBS Precision Engineering (headquarters in Eindhoven, the Netherlands) is an expert in metrology and developer/supplier of ultra-high precision solutions to measurement, positioning and motion system demands. As a strategic engineering partner to some of the world's best manufacturing equipment and scientific instrument suppliers, IBS has a distinguished track record of proven and robust precision solutions. For IBS, the ALICIA project was a follow-up to the metrology software it provided for assembly machines for the original ALICE detector.

### **ALICE**

As part of the Large Hadron Collider (LHC), ALICE is a general-purpose, heavy-ion detector. ALICE (A Large Ion Collider Experiment) was designed to address the physics of strongly interacting matter, and in particular, the properties of the quark-gluon plasma, using nucleus-nucleus collisions at high energies. This plasma approximates the conditions in the universe microseconds after the Big Bang, before matter coalesced into atoms. During the operation of ALICE the highest temperature ever in a physical experiment was achieved. Focusing, amongst others, on the high-precision observation of beauty and charm quarks, ALICE yielded a mix of confirmatory and surprising results.

### **Upgrade**

To break new ground, ALICE detector performance had to be taken to the next level. In an upgrade during the LHC shutdown in 2019 and 2020, ALICE will be fitted with central barrel detectors. These detectors consist of a new high-resolution 7-layer tracker (Inner Tracking System, ITS) based on monolithic silicon pixel detectors. A key feature of the new ITS, which is optimised for high tracking accuracy at low transverse momenta, is the very low mass of the three innermost layers. The silicon material budget per layer is reduced by a factor of seven in comparison to the present ITS; this is

particularly important for improving the impact parameter resolution. The upgrade will greatly improve the specifications of the ALICE sensors, including spatial resolution, tracking efficiency and read-out rate capabilities.

### **Chips**

The new ITS consists of seven concentric layers of pixel detectors, so-called Monolithic Active Pixel Sensors (MAPS), based on a 0.18 $\mu$ m CMOS process. The basic MAPS element is a pixel chip, provided by the Korean chip manufacturer Furex. Each chip consists of a single silicon die, measuring about 15 mm x 30 mm, and the electronics that perform signal amplification, digitisation and zero-suppression. The silicon die is built on a high-resistivity silicon epitaxial layer (sensor-active volume), which incorporates a matrix of charge collection diodes (pixels, 0.5 million per chip) with a pitch of the order of 30  $\mu$ m. Pixel size is reduced with a factor of more than 20 compared to the present ITS. Only when a particle has crossed a pixel, there will be data transmission, including the characteristics of the detection.

### **Manufacturing**

The ITS detectors comprise of sensor modules, i.e. frames each containing 14 chips. In total, some 2,000 frames have to be manufactured, each frame taking several hours of assembly time. Given the exacting demands on the sensor modules and the fragility of the chips, assembly has to be fully automatic for maximum precision, consistency and yield. This massive production job has been divided over CERN (Switzerland) and seven of its partner institutes, in Bari (Italy), Liverpool (UK), Pusan (Korea), Saclay/Paris (France), Saint Petersburg (Russia), Strasbourg (France) and Wuhan (China). Naturally, CERN took the lead in selecting the development and construction partner for realisation of the assembly machines, but in the end several institutes took care of contracting their own assembly machine.

### **Multifaceted project management**

“For all at IBS it was great to be part of the big CERN story, and to contribute to the quest for fundamental particles. We collaborated with people all over the world from widely varying backgrounds who are now all using our machines. This required extensive communication skills as we were in charge of overall project management, in close alignment with CERN. All the partners came with their own way of working in an either highly organised or a more improvisatory environment. They were based in either a university department or a dedicated research institute, with differences in the level of their facilities, concerning for example cleanroom control. But together we managed to create an open atmosphere with knowledge and expertise sharing.

Based on our track record, we were confident that we could deliver the machine, but I am proud of the feedback CERN gave us, with a positive evaluation of the excellent technical performance of ALICIA. Our story with ALICE – in a triangular ‘collision’ with CERN and the partner institutes – has not yet ended, as we are building another, eighth, machine and providing support where necessary. However, we do understand that when we hand over a fully operational machine the story begins for the researchers who will use it. Just like particle collisions this will hopefully result in an exciting cascade of new results.”

*Ivo Hamersma, ALICIA system engineer at IBS*

### **Contracting**

Based on its system engineering and machine building capabilities, metrology expertise and history with CERN concerning the metrology software for the original ALICE sensor assembly machines, IBS Precision Engineering won the contract with CERN. It involved the development and construction of an automatic assembly system called ALICIA (acronym for ALICE Integrated Circuit Inspection and Assembly machine). It was the biggest ever assignment by CERN in the Netherlands. The CERN machine is designated for the manufacture of the modules for the innermost layer, entailing the highest

demands on assembly accuracy. To a large degree the machines built for the partner institutes are copies of the first machine delivered to CERN, but some machines have been provided with different options.

### **Design**

The automatic assembly system is to produce the sensor modules by high-accuracy sensor array positioning and interconnect. IBS made up a detailed model-based design of the machine based on proven technologies for metrology, pick & place and inspection. The machine was given a modular structure so that it is easy to integrate different processes and exchange tools in case of new insights or changing user requirements. Given the wide variety of institutes for which the machine was being developed, great emphasis was put on the user perspective in the design process.

### **Interconnect**

ALICIA has to pick up each (fragile) chip, which is only 50 or 100  $\mu\text{m}$  thick, from a supply tray and place it accurately on a chuck using position markers measured by the vision system. After inspection the chip is placed on the frame, i.e. a flexible printed circuit, and ALICIA provides all interconnects, in total 67 per chip. Initially, ultra-precision laser soldering of the interconnects was considered. However, this option was discarded and an alternative was elaborated: a combination of glueing and wire-bonding. The glueing application was developed by the Italian team from the Istituto Nazionale di Fisica Nucleare, Bari. They delivered the glueing tool to the other institutes, for integration on their ALICIA copy, and provided an operator training for this tool. The interconnect procedure is the limiting factor for the throughput of the assembly process.

### **Flexibility**

“The biggest challenge in this project was system integration, in combination with flexibility. The specifications by CERN included some 500 parameters and these were still subject to change during our design phase. For example, in the development phase six different chip lay-outs were considered. The final chip design was determined while the machine design was well under way.

So, a lot of flexibility was required from our side and we incorporated this flexibility as much as possible in the design to accommodate last-minute changes. In fact, on some aspects we took the liberty to exceed the specifications in anticipation of future CERN demands. The foundation underlying this flexible approach is the rigorous procedure for process qualification that IBS follows.”

*Theresa Spaan-Burke, innovation director at IBS*

### **Accuracy**

In order to give ALICE the required accuracy, the position of the individual chips with respect to the local reference markers is crucial. Therefore, a high-accuracy ( $< 0.1 \mu\text{m}$ ) image system was developed to measure both the reference and chip marker, determining the final positioning of the chip. In combination with high reproducibility of the lateral X and Y axis, the chip can be manipulated with submicron accuracy, achieving a final assembly accuracy of  $< 5 \mu\text{m}$  over the full array of chips. These specifications help to achieve the required accuracy for determining the paths that particles have travelled. In the vertical (Z) direction, a flexure in combination with a high-resolution displacement sensor is used to accurately determine first contact with the chip, to avoid damaging the delicate chips. To exclude operator-dependency effects in the output, IBS provided the machines with self-learning capabilities which facilitate automatic calibration.

### **Inspection**

Each individual chip, provided with a unique ID, has not only been tested electrically but also undergoes visual inspection. This is used to reveal possible fractures that undermine structural integrity and determine the cleanliness (dust or particles on the chip surface). Also, the dimensions of the chip are measured with a required accuracy of better than  $0.8 \mu\text{m}$ . The inspection software uses the results for

either accepting or discarding each chip. In addition, based on the inspection results against set tolerances, the optimum position of a chip in the module can be determined, i.e. chips with highest performance are placed in critical areas of the detector. After precise assembly, final inspection of the sensor modules is required to guarantee their faultless operation. This pertains to the electronics as well as the mechanics.

### **Pusan National University (PNU), Korea: “Wonderful job”**

“We study the initial state of the universe through high-energy heavy ion collision experiments, and in particular we are interested in liberated quarks in the quark-gluon plasma. In 2009, we joined the ALICE experiment and in 2012 we could convince our government to allocate budget for the ALICE-ITS upgrade, so that we as researchers could contribute to new detector hardware. With the aid of a Korean company we developed probe cards for the electrical testing of all ALICE-ITS silicon sensor chips in Korea, at PNU and at Yonsei University. This was a big challenge because the chips are very thin and require sensitive handling.

IBS integrated the probe card in the ALICIA machine, which we will also use for the assembly of sensor modules, and taught us how to integrate the card in other ALICIA machines. Ivo Hamersma and one of his IBS colleagues visited PNU. They installed the machine perfectly, explained its operation from a to z, and provided us with a manual and training. When problems occurred we were able to solve them with the help of IBS.

This is a very international project. Together, CERN, the Korean company, IBS and our team are doing a wonderful job. I appreciate everyone’s contribution, including that of my students. I am sure we will complete testing of the chips and the assembly of sensor modules on schedule in autumn 2018. In March 2017, during the official ceremony for the tenth anniversary of the collaboration between CERN and Korea, I presented ALICIA and the industrial collaboration. The audience was very much impressed and our Ministry was happy. If everything goes well after the upgrade in 2020, we hope to see liberated heavy quarks.”

*In-Kwon Yoo, professor of Physics, and Bong-Hwi Lim, Ph.D. student*

### **Data**

The whole assembly and inspection procedure of one sensor module generates 0.5 terabytes of information. The collection and processing of this amount of big data was an additional challenge IBS had to resolve. The inspection results are analysed real time and presented via a simple graphical interface to the operator, who has to decide on the final go/no go. As soon as an assembly leaves the machine the data are transferred to a central CERN database, for potential future reference. These data are added to the data on the electrical testing of all chips, which is mainly performed at the two Korean sites, but to some extent also at other sites.

### **Commissioning**

After the first machine passed the site acceptance test at CERN, IBS undertook construction of another six systems, for which upgrades and software expansions were included. All systems passed their respective site acceptance test successfully. At delivery of each machine IBS provided a one-day operator training. To guarantee undisturbed operation – the time schedule towards the actual ITS upgrade starting in 2019 is tight – IBS provides online machine support to each production site.

### **Conclusion**

A total of seven sensor module assembly systems machines were commissioned within a tight time schedule and the eighth machine is due for end of this year. With seven ALICIA up and running, IBS has once again demonstrated its systems engineering, metrology and project capabilities, in particular featuring multifaceted project management. Data management and communication in an Industry 4.0 fashion was one of the valuable learning areas for IBS. Key success factors of the ALICIA development

project were system integration, multicultural communication and flexibility. With ‘beautiful and charming’ ALICIA, IBS has helped CERN and partner institutes take the next step in unravelling the mysteries of quark-gluon plasma physics.

**CEA, Saclay/Paris, France: “Easy to understand and extremely logical interface”**

“CEA has been collaborating with CERN for 30 years and has been participating in the ALICE experiment since its inception. We built a muon spectrometer for ALICE to study the decay particles called hadrons of muon pairs and were involved in the upgrade for which brainstorming already started in 2005-2006. Our contribution is twofold: an upgrade of the muon chambers read-out electronics and the fabrication of a new detector called MFT (Muon Forward Tracker). We will use the ALICIA machine from IBS for the assembly of MFT sensor modules, just like it is done for the ITS upgrade.

Their machine is easy to understand. Its complexity is hidden beneath an interface which is extremely logical. There is a lot of protection in the procedures, so that even when mistakes are made no major problems can occur. That’s important, because the assembly teams are composed of people from different backgrounds and with different experience levels.

We had no previous experience with IBS but we are very positive about the collaboration, especially in the one week in which they installed the machine at CERN, where we assembled our first prototype of sensor modules. They trained our team and helped to solve any problem. There was a good synergy between our teams, which we hope will continue during operation.”

*Stefano Panebianco, project leader, and Cyrille Vuillemin, research engineer*

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