Contribution to the construction of the CMS Tracker Endcaps (1)

B. Clerbaux, J.-P. Dewulf, G. De Lentdecker, J. D'Hondt, R. Goorens, J. Heyninck, T. Mahmoud, B. Meerschaut, L. Neukermans, S. Tavernier, F. Udo, C. Vander Velde, P. Vanlaer, L. Van Lancker, C. Wastiels, J. Wickens, Inter-university Institute for High Energies (IIHE) - Université Libre de Bruxelles (ULB) and Vrije Universiteit Brussel (VUB)
W. Beaumont, E. De Langhe, Universiteit Antwerpen (UA)
S. Assouak, G. Berger, L. Bonnet, C. Delaere, B. de Callatay, E. Forton, Gh. Gregoire, T. Keutgen, V. Lemaître, M. Loiselet, D. Michotte, O. Militaru, K. Piotrkowski, X. Rouby, G. Ryckewarts, D. Teyssier, O. Van der AA, M. Van der Donckt, Center for Particle Physics and Phenomenology (CP3), Université Catholique de Louvain (UCL)

Belgian Physics Society - French Physics Society, International Scientific Meeting, Lille, August 29 - September 2, 2005

1 The CMS Tracker and the Belgian contribution

The Compact Muon Solenoid or CMS detector has been designed as a multipurpose detector to study proton collisions at the Large Hadron Collider at CERN. The experiment will extend our understanding of contemporary elementary particle physics, via precise measurements to test the consistency of the Standard Model, the possible discovery of the Brout-Englert-Higgs boson and via searches for new physics beyond the Standard Model. Essential ingredients in obtaining these objectives are the measurement and identification of muons, electrons, photons and jets over a large energy range. Experience has shown that robust tracking and detailed vertex reconstruction within a strong magnetic field are powerful tools to reach these objectives.

The CMS tracker is designed to reconstruct isolated high p_T muons and electrons with an efficiency above 90% and a momentum resolution of about 2%. The geometric acceptance is $|\eta| < 2.4$. B-hadrons decaying a few mm away from the primary proton-proton interaction are also reconstructible thanks to a precise measurement of the track impact parameter (50μm). Silicon Pixel detectors provide 2-3 high-precision 3D measurements closest to the beam, and Silicon Strip detectors provide 9-14 precise measurements in the $R\phi$ projection, half of them with stereo information. The total active surface amounts to ~ 200 m^2 and about 10^7 channels are read out.

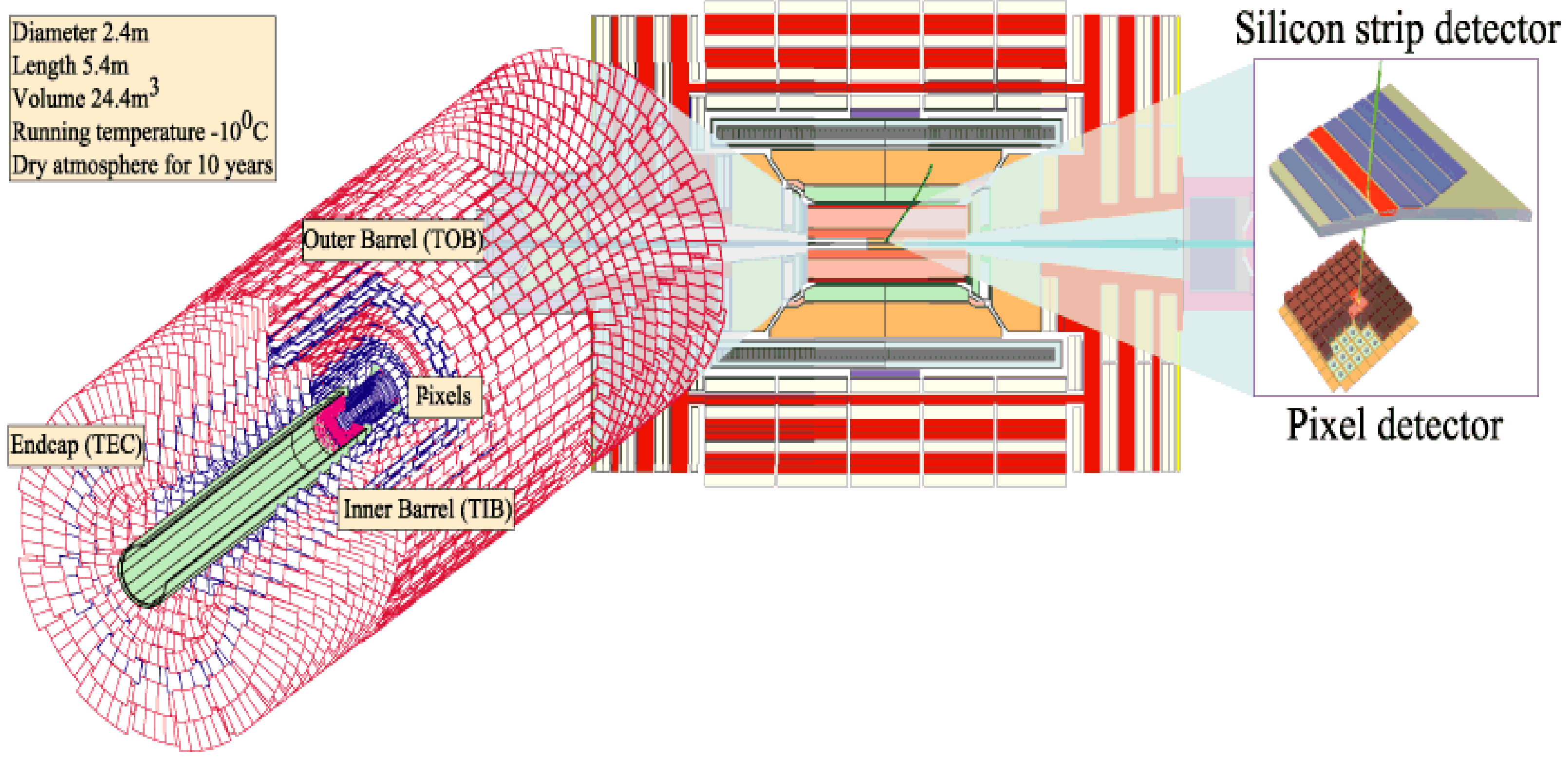

Figure 1: Schematic overview of the CMS Tracker showing all detector modules (left), the Tracker location in the CMS detector (center) and the Tracker detector technologies chosen (right).

The Belgian experimental High-Energy groups (Center for Particle Physics and Phenomenology (CP3) - Université Catholique de Louvain, Inter-university Institute for High Energies (IIHE) - Université Libre de Bruxelles / Vrije Universiteit Brussel, Université de Mons Hainaut, Universiteit Antwerpen) are involved in the construction of the Silicon Strip Tracker endcaps. This forward detector consists of about 7000 trapezoidal silicon detectors assembled onto 18 support wheels, each wheel being subdivided in 16 sectors of up to 28 modules.

In these two posters, the Belgian contribution to the construction of the CMS tracker is highlighted. The first poster describes the contributions to the design, production and validation of the silicon detector components, as well as to the assembly of the detectors. The second poster describes the contributions to the design, production and validation of the sectors (called Petals) of the Silicon Strip Tracker endcaps.

2 Silicon detector components

The CMS silicon strip detectors are composed of 1 or 2 silicon sensors and a readout circuit with integrated amplifiers, glued onto a lightweight carbon fiber or graphite support frame (see Figure 3). These components are designed by members of the CMS collaboration and produced by industrial partners.

Frames The detector frames are made either entirely of graphite or of two carbon fiber legs and one graphite crosspiece. This material is rigid and prevents in-plane displacements of the components by more than ten microns. It also has a high thermal conductivity in order to transmit the heat, generated by the electronics, to the detector cooling circuit. On one of the legs a kapton circuit is glued, that carries the high voltage to the sensor backplane.

For the tracker endcaps, the IIHE is responsible for assembling 5500 out of the 7000 TEC frames, as well as for the procurement of the frame material for the whole silicon strip tracker. The IIHE is in charge of measuring/checking the thermal conductivity of the frame material for samples of each different batch during the phase of the tracker production. Tests of module deformations with thermal cycles are performed in order to check that differential expansion between the frames and the silicon sensors did not cause an out-of-plane deformation by more than 200 μm value.

Pitch adapters The distance between the p^+ implant strips has to be matched to the picth of the integrated readout channels. In addition, this distance varies with the module position in order to maintain a constant channel occupancy. Pitch adapters of 24 different designs have been drawn at the IIHE. They consist of aluminium strips engraved on glass by photolithography. The IIHE is also responsible for the procurement and the tests of most of the pitch adapters.

Silicon sensors The CMS Silicon sensors have been carefully designed to stand the harsh radiation environment foreseen at the LHC (2.4 10^{14} 1-MeV-equivalent n/cm^2 accumulated in 10 years for the innermost detectors). An efficient quality assurance procedure is required in order to ensure the quality and the stability of the industrial production. About 1% of the total sensor production (300 full-size sensors) and 3% of the accompaniyng test structures (1200 pieces) are exposed throughout the production period, to irradiation doses equivalent to more than 10 years of LHC operation. The UCL group contributes to this quality assurance process using the high-intensity, fast (few MeV) neutron irradiation facility available in Louvain-la-Neuve, able to deliber a dose equivalent to 10 years of LHC operation within a few hours.

The radiation damages are evaluated from the electrical characterization of silicon sensors (CV, IV, resistances up to 5 GOhm and capacitances measurements down to 0.1 pF). The electrical test bench is built around a PA-200 Karl Süss probe station surrounded by many test instruments (LCR-meter, voltage/current source, electrometer, data/switch unit and bias supply) controlled by a PC-computer through GPIB-interfaces. The environment (relative humidity, chuck temperature) is continuously monitored.

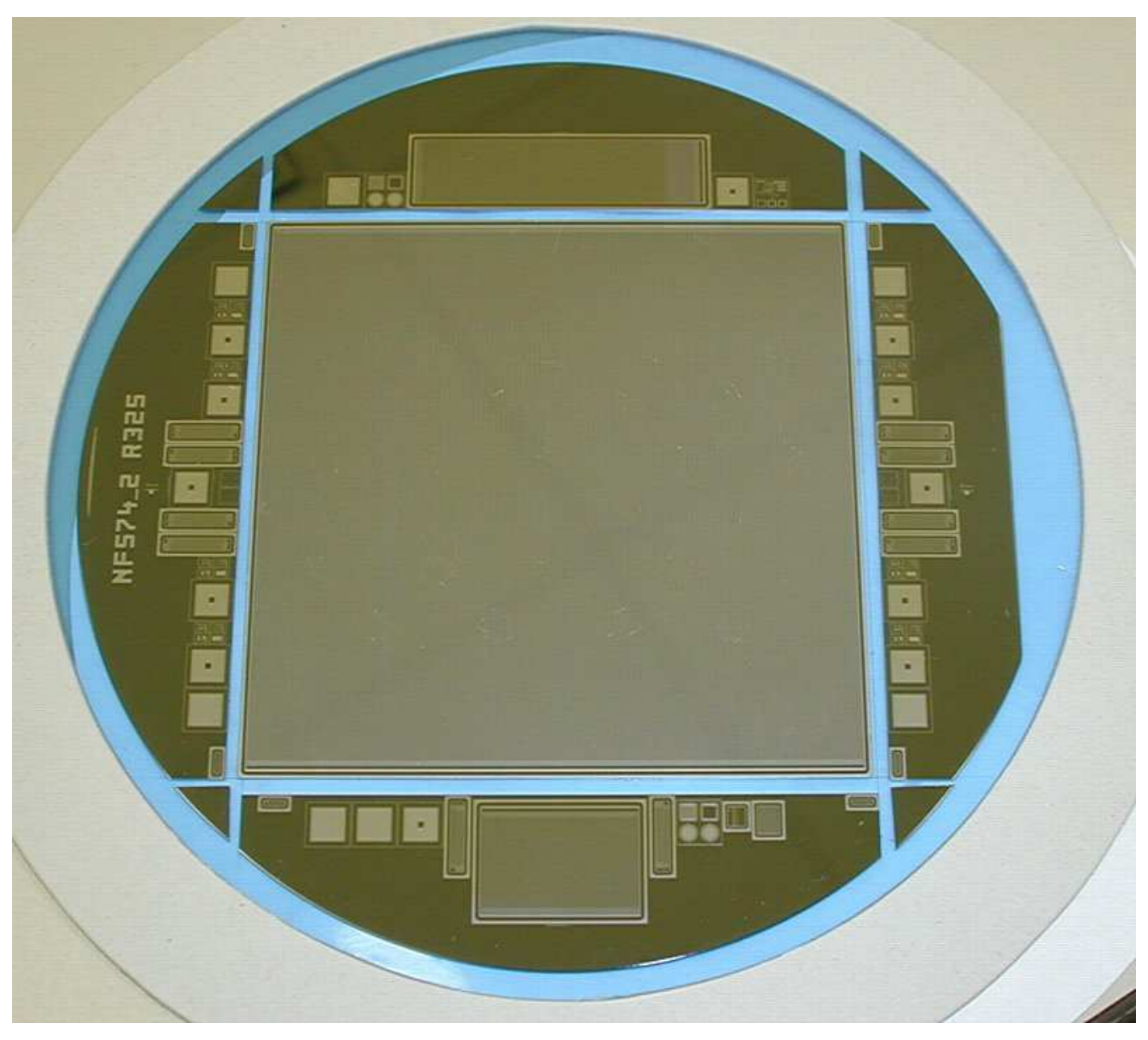

Figure 2: CMS 8-inch Silicon wafer with a sensor (square at the center) and the remaining cut-offs with test structures (half-moons).

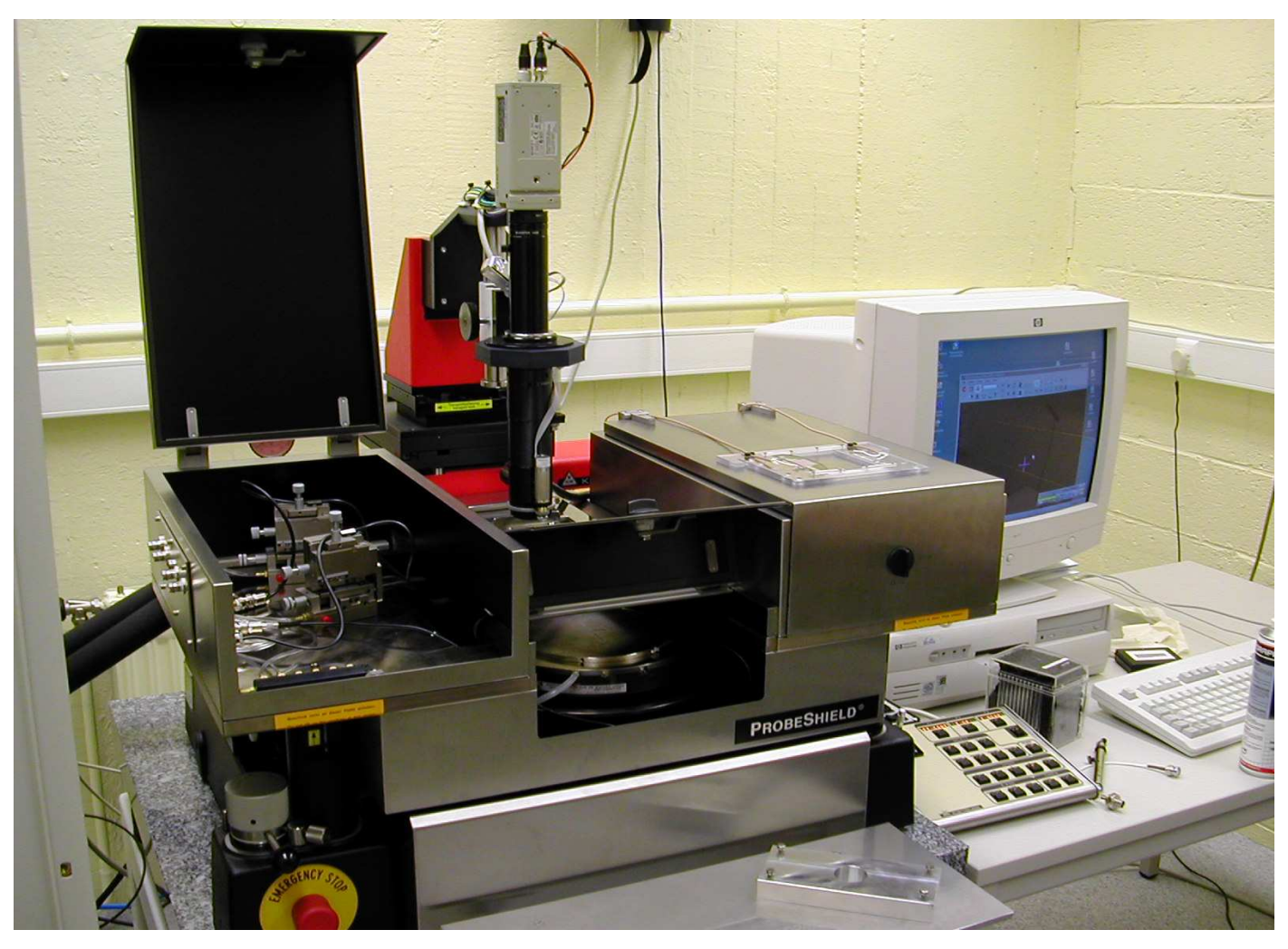

Figure 3: Probestation used to measure the electrical characteristics of the sensors before and after irradiation.

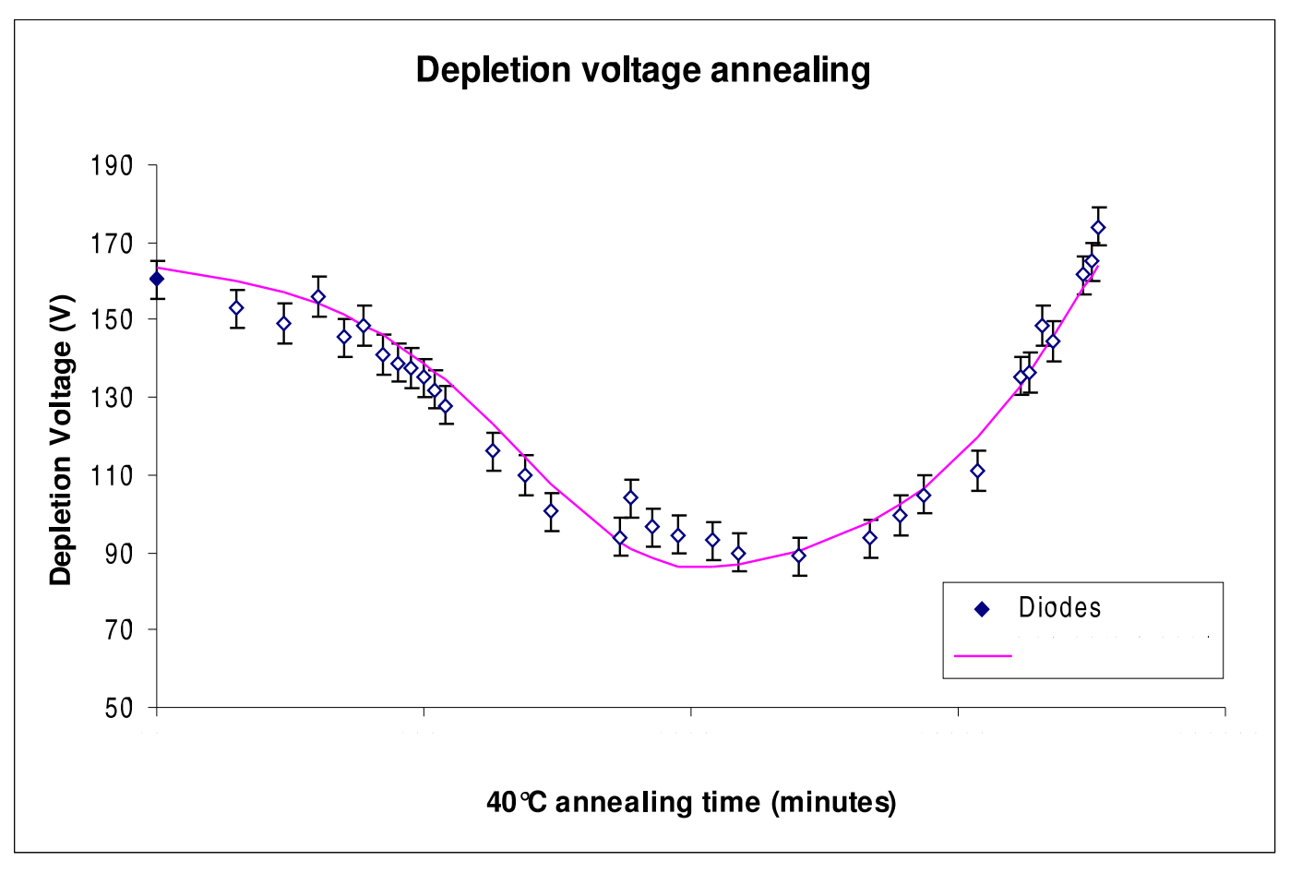

Figure 4: Evolution of the depletion voltage after exposure to nominal LHC fluence (annealing), and comparison to simulation results from the ROSE collaboration.

Readout circuits The readout circuits consist of integrated amplifiers mounted onto multilayer polyimide hybrids and connected by ultrasonic microbonding. Each hybrid carries 4 or 6 APV25 amplifier chips with 128 readout channels each, a multiplexing chip and a control chip which handles the clock and trigger signals, monitors the electronics bias voltages and currents, and the sensor temperature through a 12bit ADC. The chips are addressed using the I2C protocol. For radiation hardness the chips are produced using a 0.25 μm submicron process.

The UCL contributed to the development of an industrial fast tester, called FHIT, for the qualification of the hybrid production and for fast test during module and petal assembly. The hybrid tests include basic connectivity, electrical and functional tests. The first part checks all the connectivity of the chips and hybrid components and searches for short and open circuits between power lines. Then, the power consumption and I2C access of chips is checked during the electrical test, as well as the calibration of the 12bit ADC DCU chip. Finally, all the basic functionalities, like channel pedestal, gain, raw and common-mode substracted noise are tested during the functional test. The test with the FHIT setup is fully integrated into the industrial production of the front-end hybrids.

Figure 5: Front-end Hybrid Industrial Tester (FHIT) setup with 2 hybrids during a dual test in industry.

3 Assembly of the modules

The IIHE is in charge of assembling about 1500 tracker modules of four different types : Ring 3, Normal Ring 5, Stereo Ring 5 and Ring 6. An automated Silicon Module assembly system for the CMS Tracker is used to ensure the precision. The setup consists of a high-precision robotic positioning machine (Aerotech AGS 10000 Gantry) which provides a large static area, 4 separate coordinate positioning motors (X, Y, Z and ϕ rotation), and control hardware and software. The Gantry robot is illustrated in Figure 3 together with an assembled Ring-3 module.

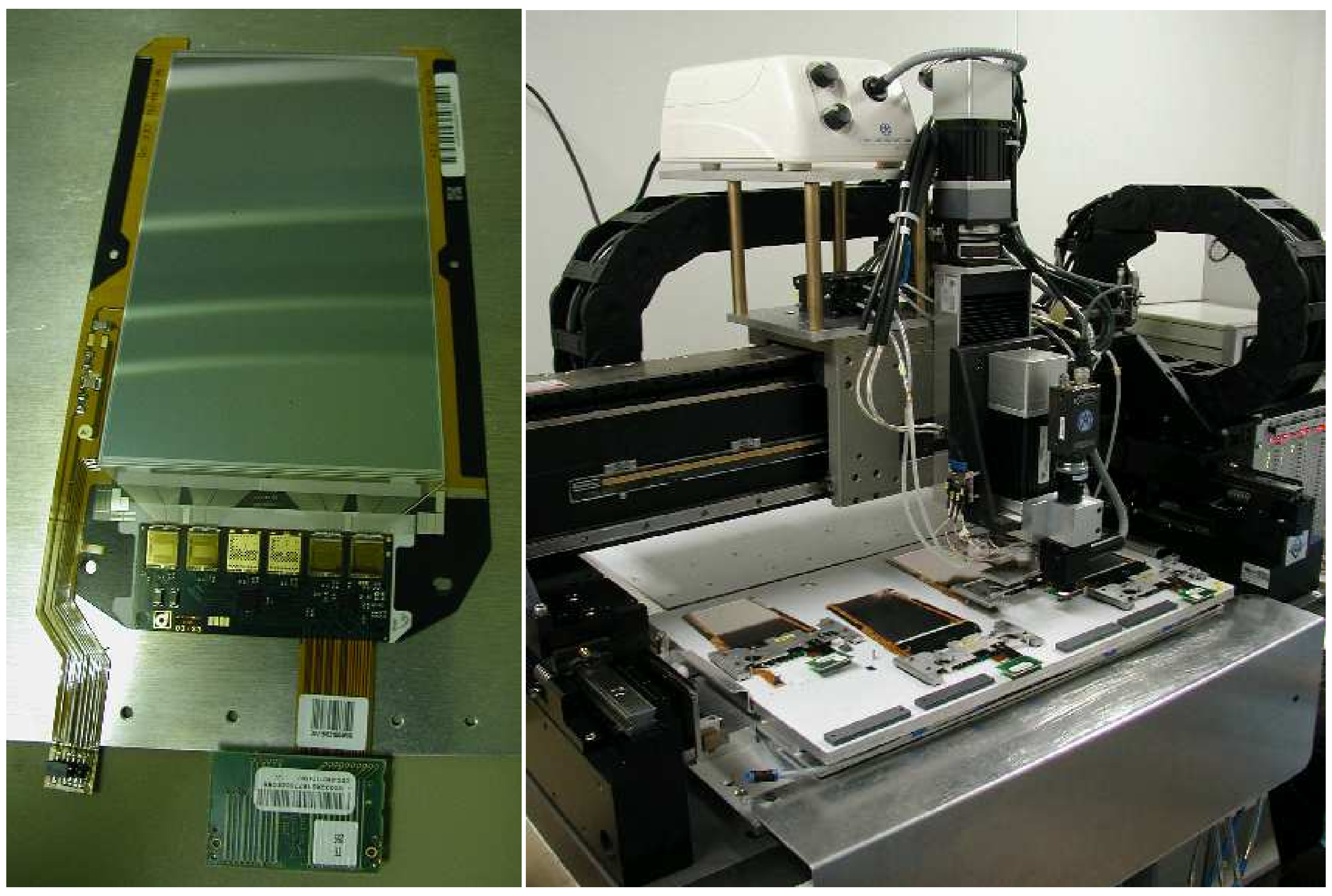

Figure 6: Illustration of an assembled module on the left and the Gantry robot at work on the right. The X-axis used in the plots below points from one side of the module to the other (left to right), while the Y-axis is parallel with the sensor strips (bottom to top).

The effective area of the Gantry is calibrated by a 2D grid of points measured with a high precision Mitutoyo machine. This grid is remeasured with the Gantry and used as the coordinate reference system. Several independent grids were used and the local systematic effect was estimated to be of the order of 5 μm.

A pattern recognition of a CCD camera image is used to measure the position of the sensors and the hybrids. Each module frame is positioned on the assembly plate by 2 precision 3H7 steel pins of which the position is precisely known. The nominal positions of the module components are calculated relative to these pin positions.

The repeatability of the positioning of the assembled modules is good, an RMS of 4 μm is obtained for the fiducial marks on the sensors. Remeasuring the module on a different place within the calibrated region of the Gantry, and using therefore different pins and their assigned position, results in differences of the order of 5 μm. Batches of modules are remeasured on an independent measuring machine at the CERN Metrology Service and in Aachen, and are found to be in agreement with the measurements on the Gantry. In addition, several modules are re-measured on gantries from other centers (in Lyon and Fermilab) and the position measurements agree within few μm. The number of modules already assembled in Brussels is 550. With respect to the precision tolerances defined by the CMS collaboration, the yield is 90% when considering only Grade-A modules and 94% when including Grade-B modules (slightly out of tolerances but useable in the experiment).

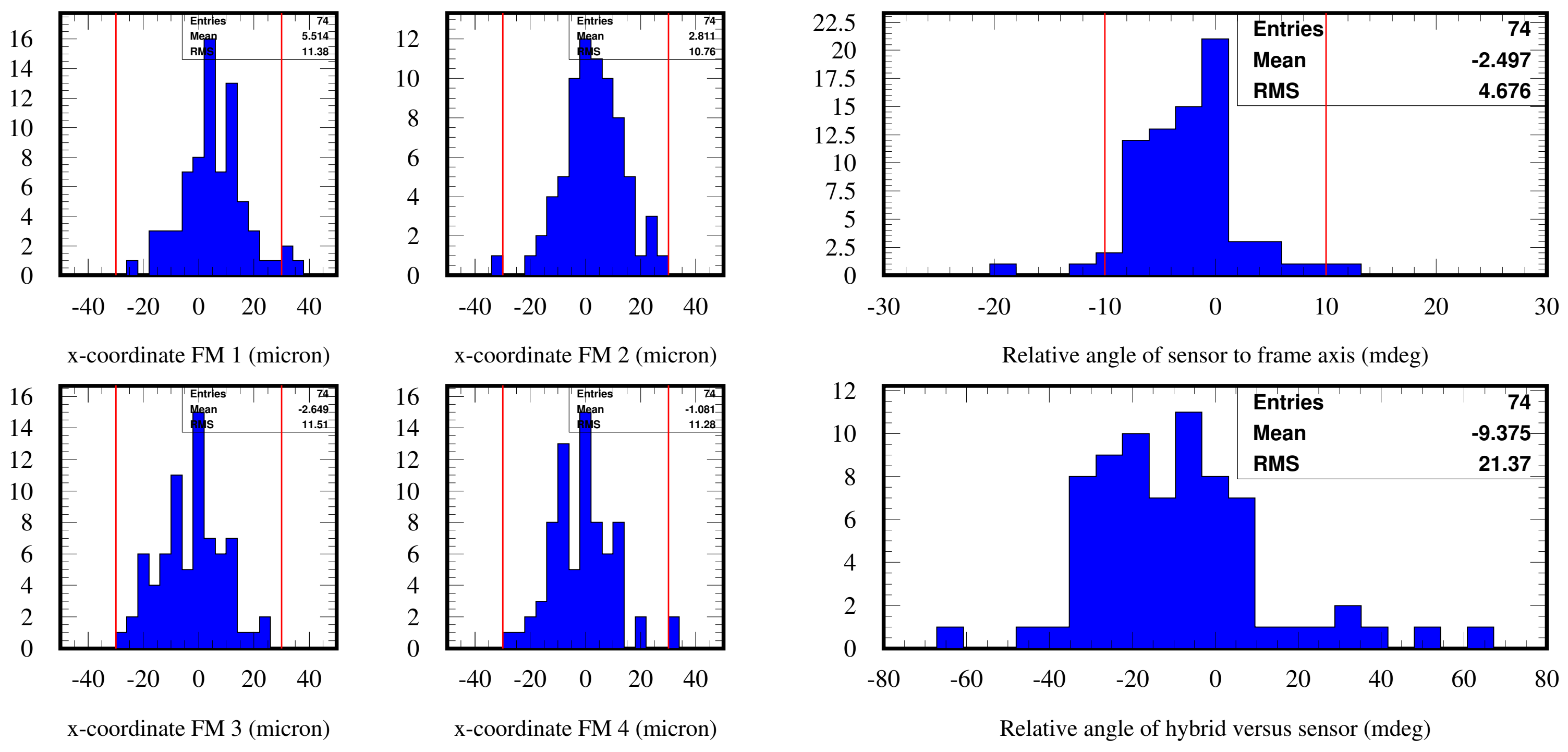

Figure 7: Assembly precision achieved for a sample of 74 Ring-3 modules, as measured from the 4 fiducial markers (FM) located in each corner of the sensor. The axes are defined in the caption of Figure 3, while the CMS specified precision limits are indicated by the red borderlines.