The LHCf Si tracking system: implementation and performances

S. Ricciarini*, **O. Adriani**†, **L. Bonechi**†, **M. Bongi***, **G. Castellini**‡, **R. D'Alessandro**†, **K. Fukui**§, **M. Haguenauer**¶, **Y. Itow**§, **K. Kasahara**‖, **D. Macina****, **T. Mase**§, **K. Masuda**§, **Y. Matsubara**§, **H. Menjo**§, **M. Mizuishi**‖, **Y. Muraki**††, **M. Nakai**‖, **P. Papini***, **A.-L. Perrot****, **T. Sako**§, **Y. Shimizu**‡‡, **K. Taki**§, **T. Tamura**[x], **S. Torii**‖, **A. Tricomi**[xi], **W.C. Turner**[xii], **A. Viciani***, **K. Yoshida**[xiii]

*INFN Sezione di Firenze, Firenze, Italy
†Università degli Studi di Firenze and INFN Sezione di Firenze, Firenze, Italy
‡IFAC CNR and INFN Sezione di Firenze, Firenze, Italy
§Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan
¶École-Polytechnique, Palaiseau, France
‖Research Institute for Science and Engineering, Waseda University, Tokyo, Japan
**CERN, Geneva, Switzerland
††Konan University, Kobe, Japan
‡‡Institute for Cosmic Ray Research, University of Tokyo, Japan
[x]Kanagawa University, Yokohama, Japan
[xi]Università degli Studi di Catania and INFN Sezione di Catania, Catania, Italy
[xii]LBNL, Berkeley, California, USA
[xiii]Shibaura Institute of Technology, Saitama, Japan

***Abstract*. The LHCf experiment is formed by two sampling EM calorimeters to study energy and transverse momenta of photons and π^0 emitted from p-p collisions at LHC (14 TeV center-of-mass energy) along both directions in the very-forward region; this measurement will give a precise calibration for hadron interaction models describing air showers initiated by very high energy cosmic-rays.**

The Si tracking system of LHCf is composed of 4 pairs of single-sided microstrip sensors (160 μm read-out pitch), integrated within one of the two calorimeters, interleaved with calorimeter layers (W absorber and scintillator planes); its purpose is to determine the shower transverse profile with uncertainty of few tens microns.

The 3072 microstrips are read-out through high-dynamic-range (400 MIP nominal) PACE3 chips, originally designed for the CMS Si Preshower detector; PACE3 output signals are digitized and processed by a set of fast dedicated ADC-FPGA electronics boards and transmitted to the LHCf storage system via optic fiber channels.

The performances of the Si tracking system were measured at the CERN SPS H4 beam line in 2007, using 50-200 GeV electrons, 150-350 GeV protons and 100-150 GeV muons; the results of this beam test confirmed the spatial resolution expected from design and its energy dependence: for incident electrons in the energy range of interest (above 100 GeV) the resolution is better than 100 micron and improves with increasing energy.

***Keywords*: electromagnetic shower, tracking system, LHC.**

I. Introduction

The LHCf experiment [1] is composed of 2 independent detectors, conventionally called Arm1 and Arm2 (Fig. 1), installed on the opposite sides of the ATLAS interaction point IP1 at LHC accelerator (CERN), along the beam line and 280 m away from each other in a location where all the charged particles coming from the collision are swept away by the beam separation dipole.

The detectors are able to identify and precisely measure the energy and transverse momentum spectra of neutral particles produced very forward in 14 TeV proton-proton interactions, namely single photons and γ pairs from decays of π^0 or neutrons, in the energy range from 100 GeV to 7 TeV. To accomplish this task, each detector was designed as an electromagnetic calorimeter with fine longitudinal granularity, measuring the total energy of the incident photons, with an integrated tracking system to determine the impact point, implemented with plastic scintillating fibers for Arm1, and with Si microstrip detectors for Arm2. To better identify the two γ from π^0 decay, both Arm1 and Arm2 are divided in two independent calorimetric towers; with the tracking system it is possible to select clean events where only one photon has showered in each tower.

Each calorimetric tower consists of W plates interleaved with 16 layers of 3 mm thick plastic scintillators, with a total thickness of 44 radiation lengths (X_0) or 1.7 interaction lengths (λ). The calorimetric tower located on the beam axis is smaller, to reduce the rate of particles to an acceptable level. A crucial characteristics of LHCf detectors is compactness since they are housed inside a 96 mm wide gap where the single beam pipe from

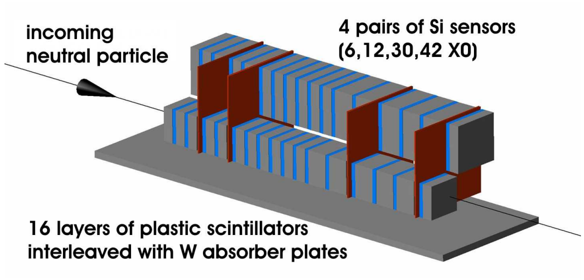

Fig. 1: Schematic drawing of the LHCf Arm2 calorimeter. The two towers are 24 cm long and have transverse dimensions of 2.5×2.5 cm^2 and 3.2×3.2 cm^2.

the interaction point splits into two separate beam pipes used to circulate the two proton beams along the LHC ring.

In what follows the Si tracking system of Arm2 will be described in its main components: the Si detectors (section II), the front-end (FE) electronics (section III) and the data acquisition system (section IV). Finally in section V the main performances of the Si tracking system will be discussed.

II. The Si detector module

The Si tracking system of LHCf, positioned within the Arm2 calorimetric structure, is formed by 4 pairs of Si microstrip sensors located at depths of 6, 12, 30 and 42 X_0 from the upstream surface of the calorimeter.

Each sensor is a 285 μm thick n-type microstrip wafer with 6.4×6.4 cm^2 total surface area, covering the entire cross section of both Arm2 towers; the sensors are identical to those used in the ATLAS experiment for the barrel part of the Semi-Conductor Tracker (SCT) [2]. A sequence of 768 p^+ microstrips with 80 μm pitch is implanted on the junction side; the read-out pitch is 160 μm, thus reducing the total analog channels to 384 per sensor (for a total of 3072 channels) but still allowing a very fine sampling of the transverse cross section of electromagnetic showers and in particular reducing saturation of read-out channels. The sensor is completely depleted by applying a 150 V bias voltage.

A compact mechanical structure, called Si detector module (Fig. 2), integrates each pair of Si sensors, with implanted strips orthogonal to each other, together with the corresponding FE electronics housed on a Front End Hybrid (FEH).

The Si module has a central 500 μm thick supporting Al layer; on each side of this layer, a Si sensor on a fiberglass pitch adapter circuit and the corresponding FEH with a kapton fan-out circuit are glued. For each read-out channel, wire bondings (25 μm Al wire) form the 3 electrical connections between the Si sensor, the underlying pitch adapter, the fan-out circuit and the FEH. The pitch adapter circuit also provides the bias voltage to the sensor backplane through a conductive glue layer. The module is covered on both sides with a light Delrin [1]

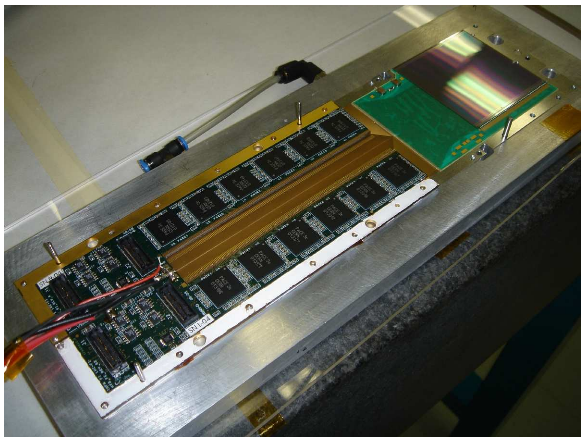

Fig. 2: Open view of one side of a Si detector module. On the left: two FE half-hybrid boards (6 PACE3 chips each) with the central area occupied by kapton fan-outs; on the right: the Si sensor, glued on the fiberglass pitch adapter.

frame on the sensor part, housing the nearby calorimetric layer; the hybrid part is instead covered by an aluminium frame, guaranteeing a good thermal path toward the lateral copper wall of Arm2 calorimeter to extract the heat produced by the FEH electronics[2].

III. The front-end electronics

The FE electronics for a Si sensor is housed in the corresponding FEH, whose design was a major undertaking given the severe space constraints (the hybrid dimensions are 8×18.5 cm^2) and relatively high number of read-out channels on the sensor side (384) and of digital control lines on the data acquisition side (≈ 160).

Each FEH is composed of two symmetric boards (called Left and Right half-hybrids), L shaped in such a way to leave a void central area to provide access to wire bonding machine for the integration with the kapton fan-out circuit. The analog and digital connections between FEH and data acquisition system (MDAQ boards, described in section IV) are implemented with low pitch, high speed connectors [3], coupled to custom made ribbon cables formed with single micro-coaxial cables to minimize crosstalk between adjacent signals.

The FEH houses 12 PACE3 [3] integrated circuits, containing the amplifying and multiplexing stages for the strip signals. The PACE3 chip (Fig. 3) is a radiation-hard device developed for the CMS Si Preshower Detector, which was selected here because of its optimal linearity, speed and noise performances for use in the Arm2 detector. It is a synchronous analog sampler specifically designed to work with the LHC 40 MHz machine clock, with 32 input channels and analog memory pipelines, read through an analog multiplexed output.

[1] Polyoxymethylene from Dupont (www.dupont.com).

[2] The total power dissipated by the tracking system FE electronics is about 60 W.

[3] Model QSE/QTE from Samtec (www.samtec.com).

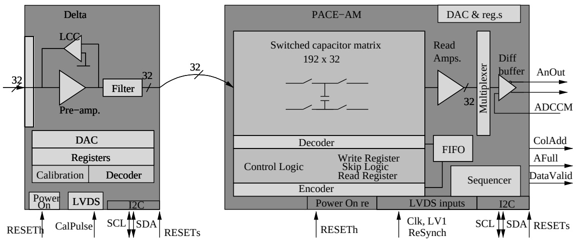

Fig. 3: Functional block scheme of PACE3 chip.

The PACE3 consists of two separate dies housed in a single chip package. The first die (called DELTA) contains the 32 independent amplifier/shaper analog chains with the calibration circuitry; the second die (called PACE AM) contains the 32 analog pipelines (192 cells deep) implemented on a switched capacitor array, and the output multiplexer. The operating parameters can be set-up and tuned by means of a digital command interface and an internal control logics with FIFO memories.

The analog outputs of the DELTA are characterized by a very fast peaking time (≈ 32 ns). The PACE AM samples these outputs every 25 ns. The phase has been properly set, with respect to the experiment trigger, to sample the pulse at its maximum.

IV. The data acquisition and control system

A. Data acquisition system

The data acquisition system of the Si detectors is formed by 4 custom made boards, called MDAQ boards, housed within an electronics crate positioned nearby the Arm2 calorimeter.

Each MDAQ board operates in parallel and independently from the others and is dedicated to acquire a whole Si detector module, corresponding to 2×12 PACE3 and 2×384 read-out channels. The MDAQ board hosts 4 ADC daughter boards, one for each half hybrid of the module. Each ADC board contains 3 dual 12-bit ADC's [4] operated at 40 Msps, which digitize the 6 PACE3 analog data outputs from the corresponding half-hybrid.

All the data acquisition operations for a MDAQ board are managed by an on-board digital control circuit, called MDAQ controller and implemented in a programmable logics FPGA chip [5]. The PACE3 chip, after receiving the trigger pulse, generates a fixed sequence of data on its analog output line, containing the signals stored for its 32 input channels on 3 contiguous cells of the analog pipeline, separated by 25 ns each; auxiliary information is also transmitted on PACE3 digital output lines. The choice of the cells to be transmitted among the 192 possible ones takes into account the fixed delay between particle crossing the detectors and generation of experiment trigger pulse from the scintillator system.

All PACE3 are thus read-out simultaneously in 6.9 μs. The data from ADC's are temporarily stored on FIFO memories as soon as they are digitized; immediately after the end of the read-out phase, the MDAQ controller sends the digitized data, along with other status information, via an optical link [6] to a custom receiver VME-standard card integrated in the LHCf experiment control system, which is installed in the ATLAS experiment control room, 200 m far from the Arm2 detector.

The total time needed for trigger processing (read-out and transmission) is 370 μs. During all the event processing a set of consistency checks of the read-out data is performed by the MDAQ controller (e. g. check of cell identifiers for PACE3 output data, check of proper FIFO operation); possible error conditions are registered in the status information transmitted together with event data.

B. Control system

The control system of the Si detectors is based on a general architecture and single devices developed for the CMS tracking system; in the experiment control room, a PCI controller card (FEC [4]) interfaces optically to a Digital Optical Hybrid Module (DOHM [5]), placed in proximity of the Arm2 detector. The DOHM receives the 40 MHz clock synchronization signal with embedded experiment trigger pulses (coded as absence of clock transitions) and the slow control signals for the configuration of the PACE3 chips and of the MDAQ boards, and sends them via an electrical token ring to each of the 4 MDAQ boards, where they are distributed by two Clock and Control Unit Modules (CCUM [6]) and a PLL [7]. The use of two CCUM per board makes it possible to implement a redundancy scheme in such a way that failure of one CCUM or even a full MDAQ board does not affect the functionality of the other boards.

V. Si tracking system performances

The precise determination of the particle impact point in the LHCf detectors (the required resolution is better than 200 μm) is of fundamental importance for the measurement of the transverse momentum and for the correction to be applied to the energy measured by the calorimeter to take into account the effect of lateral shower leakage. The spatial resolution of the Si microstrip system depends mainly on the strip read-out pitch and on the noise and linearity of the analog signal chain.

The Arm2 Si tracking system has been designed and configured to achieve a precision better than 100 μm over the whole energy region covered by LHCf (100 GeV to 7 TeV). In particular, the PACE3 working parameters have been adjusted and characterized for the present application, to assure a sufficiently high dynamic range to read-out the charge released by very energetic electromagnetic showers (up to ~ 400 MIP per channel) without significant deviation from linearity. The noise levels obtained for all the read-out channels

[4]Model AD9238 from Analog Device (www.analog.com).
[5]Cyclone II from Altera (www.altera.com).
[6]DLT6000-ST/DLR6000-ST from HP (www.hp.com), 100 Mbyte/s.

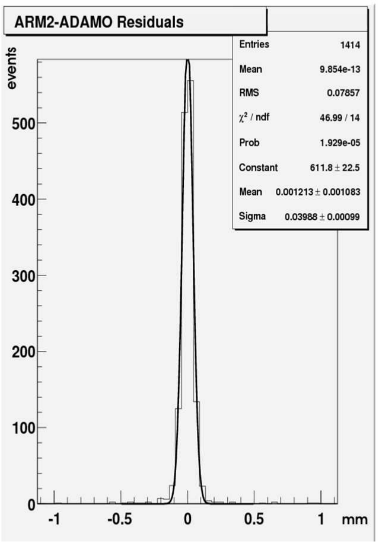

Fig. 4: Distribution of residuals for the shower centre X coordinate in the first Si module, referred to the extrapolated ADAMO telescope track. Data taken for 200 GeV electrons.

are homogeneous and ~ 0.1 MIP, corresponding to ≈ 2 ADC counts in the read-out configuration. Only one anomalous, i. e. very noisy, channel over 3072 has been found.

The achievement of the design tracking performances has been verified at the 2007 SPS beam test, where the completed Arm2 detector was qualified with charged particles (50-200 GeV electrons, 150-350 GeV protons and 100-150 GeV muons). In the SPS test setup, an external Si microstrip telescope system, ADAMO [8], has been positioned along the beam line, immediately upstream the Arm2 detector, to precisely evaluate the impact point of the incident particle. The intrinsic precision of the ADAMO telescope for the beam particles (few μm) is much better than the expected spatial resolution of the Arm2 tracking system, which can then be directly inferred by looking at differences with respect to the extrapolated track from ADAMO.

As an example, Fig. 4 shows the distribution, after the alignment of the Si tracking system, for a set of 200 GeV electrons, of the differences between the measured X coordinate of shower centers in the first Arm2 Si sensor pair (located at 6 X_0 inside the calorimeter) and the impact points extrapolated at the same depth by using the ADAMO telescope. The FWHM of this distribution, which amounts to ≈ 40 μm, gives the Si detector spatial resolution.

All Arm2 Si modules show a homogeneous behaviour. Fig. 5 shows the energy dependence of the spatial resolution for electromagnetic showers, which improves with increasing particle energy; in the energy range of interest (above 100 GeV) it is better than 100 μm, which is quite satisfying.

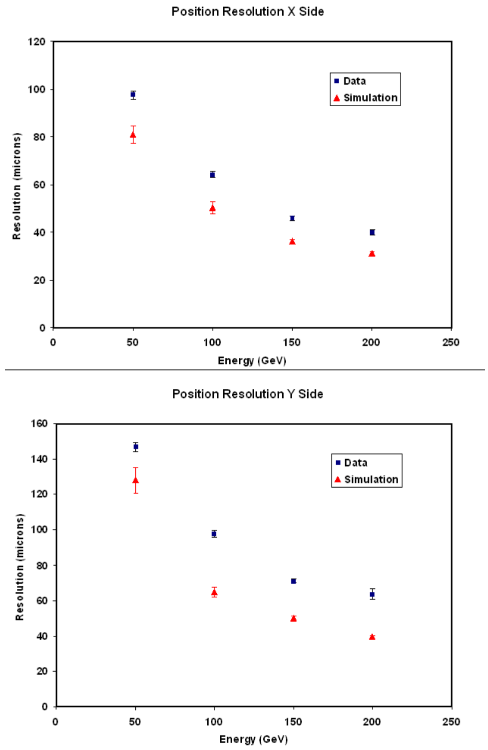

Fig. 5: X and Y position resolution, on the first Si module, for electromagnetic showers as a function of incident electron energy.

The same figure also shows predictions from simulations, which are more optimistic by roughly 20%; this is probably due to the approximate description of the charge sharing between sensor strips.

For each Si module, the Y view sensor, located downstream with respect to the X one, has a systematically worse performance; this is related to the presence, between the sensors, of an air gap where the shower expands. The different X/Y spatial resolution is correctly reproduced by simulation.

REFERENCES

[1] O. Adriani et al., *The LHCf detector at the CERN Large Hadron Collider*, JINST. 3 (2008) S08006

[2] S. Roesler et al., *ATLAS Tracker TDR*, http://home.cern.ch/sroe-sler/dpmjet3.html

[3] P. Aspell, *The Design and Development of the Front-end Electronics for the CMS Preshower Detector*, Ph.D. Thesis, Lyon (France), 2001

[4] K. Kloukinas et al., *FEC-CCS: A common Front-End Controller card for the CMS detector electronics*, Valencia 2006, Electronics for LHC and future experiments, 179-184

[5] F. Benotto et al., *Design and test of the digital opto hybrid module for the CMS tracker inner barrel and disks*, CERN-CMS-NOTE-2008-013, 2008

[6] C. Paillard et al., *The CCU25: A network oriented communication and control unit integrated circuit in a 0.25 μm CMOS technology*, Colmar 2002, Electronics for LHC experiments, 174-178

[7] P. Placidi et al., *CMS Tracker PLL Reference Manual*, CERN - EP/MIC, July 2000, Version 2.1

[8] L. Bonechi et al., *Development of the ADAMO detector: test with cosmic rays at different zenith angles*, Proc. of 29$^{\text{th}}$ Int. Cosmic Ray Conference, Pune (India), 9 (2005) 283-286