The DAMPE Silicon-Tungsten Tracker

P. Azzarello[a,*], G. Ambrosi[b], R. Asfandiyarov[a], P. Bernardini[c,d], B. Bertucci[b,e], A. Bolognini[b,e], F. Cadoux[a], M. Caprai[b], I. De Mitri[c,d], M. Domenjoz[a], Y. Dong[f], M. Duranti[b,e], R. Fan[f], P. Fusco[g,h], V. Gallo[a], F. Gargano[g], K. Gong[f], D. Guo[f], C. Husi[a], M. Ionica[b,e], D. La Marra[a], F. Loparco[g,h], G. Marsella[c,d], M. N. Mazziotta[g], J. Mesa[a], A. Nardinocchi[b,e], L. Nicola[a], G. Pelleriti[a], W. Peng[f], M. Pohl[a], V. Postolache[b], R. Qiao[f], A. Surdo[d], A. Tykhonov[a], S. Vitillo[a], H. Wang[f], M. Weber[a], D. Wu[f], X. Wu[a], F. Zhang[f]

[a] *Département de Physique Nucléaire et Corpusculaire, University of Geneva, Geneva, Switzerland*
[b] *Istituto Nazionale di Fisica Nucleare Sezione di Perugia, Perugia, Italy*
[c] *Dipartimento di Matematica e Fisica "E. De Giorgi", Univerisità del Salento, Lecce, Italy*
[d] *Istituto Nazionale di Fisica Nucleare Sezione di Lecce, Lecce, Italy*
[e] *Dipartimento di Fisica e Geologia, Univerisità di Perugia, Perugia, Italy*
[f] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[g] *Istituto Nazionale di Fisica Nucleare Sezione di Bari, Bari, Italy*
[h] *Dipartimento di Fisica "M. Merlin" dell'Univerisità e del Politecnico di Bari, Bari, Italy*

Abstract

The DArk Matter Particle Explorer (DAMPE) is a spaceborne astroparticle physics experiment, launched on 17 December 2015. DAMPE will identify possible dark matter signatures by detecting electrons and photons in the 5 GeV - 10 TeV energy range. It will also measure the flux of nuclei up to 100 TeV, for the study of the high energy cosmic ray origin and propagation mechanisms. DAMPE is composed of four sub-detectors: a plastic strip scintillator, a silicon-tungsten tracker-converter (STK), a BGO imaging calorimeter and a neutron detector. The STK is composed of six tracking planes of 2 orthogonal layers of single-sided micro-strip detectors, for a total detector surface of ca. $7\,\mathrm{m}^2$. The STK has been extensively tested for space qualification. Also, numerous beam tests at CERN have been done to study particle detection at silicon module level, and at full detector level. After description of the DAMPE payload and its scientific mission, we will describe the STK characteristics and assembly. We will then focus on some results of single ladder performance tests done with particle beams at CERN.

*Corresponding author
Email address: philipp.azzarello@unige.ch (P. Azzarello)

Preprint submitted to Nuclear Instruments and Methods in Physics Research A February 11, 2016

Keywords: spaceborne experiment, dark matter, cosmic rays, silicon tracker

1. Introduction

The DArk Matter Particle Explorer (DAMPE) is a high energy astroparticle physics satellite. It is one of the five space science missions of the "Strategic Pioneer Program on Space Science" [1] of the Chinese Academy of Sciences (CAS).

The scientific goals of DAMPE is to measure precisely the summed spectrum of electrons and positrons, and the photon spectrum between 5 GeV to 10 TeV, as well as the cosmic ray flux and chemical composition from 10 GeV to above 100 TeV. The geometrical acceptance is of $\sim$0.3 $\mathrm{m^2 sr}$, for electrons and photons, $\sim$0.2 $\mathrm{m^2 sr}$ for cosmic rays. To achieve this, a thick total absorption calorimeter is combined with a precise tracker equipped with integrated photon converter .

The DAMPE detector (figure 1) is composed of four sub-detectors. The plastic scintillator strip detector (PSD) is composed of one double-layer (one x and one y) of scintillating strips. It serves as anti-coincidence detector for photon identification, as well as a charge detector for the cosmic rays. The second sub-detector is the Silicon-Tungsten Tracker (STK) and will be discussed in detail in the following sections. The third sub-detector, the calorimeter, is made up of 14 layers of BGO bars in a hodoscopic arrangement. The total thickness of the calorimeter is equivalent to 31 radiation lengths, and 1.6 interaction lengths. The last sub-detector is the neutron detector (NUD). It is made of 16 1-cm thick boron-doped plastic scintillator plates. The purpose of the NUD is to detect delayed neutrons resulting from a hadron shower, to improve the electron/photon separation power, expected to be 10^5 overall.

Design, prototyping, production, test and qualification of DAMPE payload has been carried out by collaborating institutes of China, Switzerland and Italy.

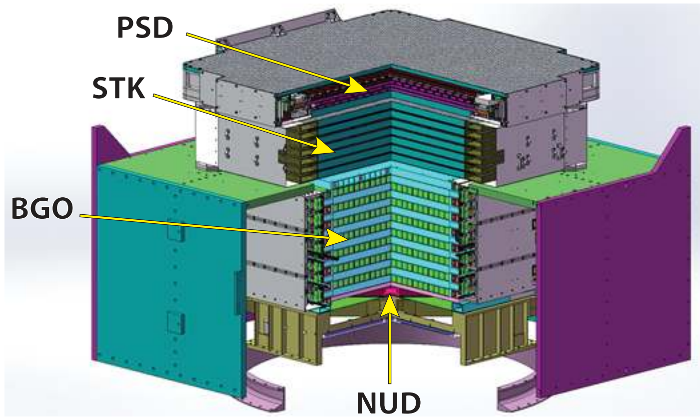

Figure 1: The DAMPE satellite payload. It is composed of a plastic strip scintillator (PSD), a silicon-tungsten tracker (STK), a BGO calorimeter, and a neutron detector (NUD).

2. The Silicon-Tungsten Tracker (STK)

The principle of the STK is based on an approach used in previous space experiments (Fermi[2], Agile [3]). Incoming photons convert to an electron-positron pair in one of the tungsten converters. The pair is then detected in the subsequent silicon layers. Multiple scattering of charged particles can be reduced by spreading the tungsten to several foils. For high energy particles ($>5\,\mathrm{GeV}$), the effect is negligible if the tungsten thickness is of a few millimeters ($\theta_0 = 0.08^\circ$ for 1 mm tungsten, and 5 GeV particles).

The STK is made of 6 tracking planes each consisting of two layers of single-sided silicon micro-strip detectors measuring the two orthogonal views perpendicular to the pointing direction of the detector. Three layers of tungsten plates of 1 mm thickness are inserted in front of tracking layers 2, 3 and 4, for photon conversion. Tracking layer 1 provides the coordinate of the entrance point of the passing particle, to be linked with the measurement of the PSD sub-detector. The absence of tungsten after tracking layer 4 allow to cleanly reconstruct the track of electron-positron pairs produced by photon conversion in the last tungsten layer.

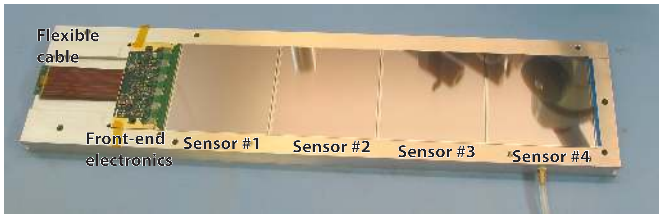

Figure 2: The silicon ladder is made of four silicon micro-strip detectors. The front-end electronics is located at one extremity of the ladder. It reads out 384 strips, with a readout pitch of 242 µm. Six VA140 ASICs are used for the signal amplification.

2.1. The silicon detector module

The DAMPE STK is composed of 192 silicon modules, named ladders, made of 4 single-sided micro-strip detectors (figure 2). The sensor strips are parallel to the ladder length, and are daisy-chained via micro-wire bonds.

The silicon detectors, manufactured by Hamamatsu Photonics [4], consists of 768 p^+-strips implanted in the n-doped bulk. The strips are AC-coupled and biased through polysilicon resistors. The dimensions of the detectors is $95 \times 95 \times 0.32\,\mathrm{mm}^3$. The detector is essentially the same as the one used in AGILE [3], except for the thickness, bulk resistivity and backside metallization (gold instead of aluminum, to improve backside contact). The bulk resistivity is $> 7\,\mathrm{k}\Omega \cdot \mathrm{cm}$, thus the full depletion voltage is 50 V at maximum. The strips are 48 µm wide and 93.196 mm long, with a pitch of 121 µm. The typical coupling capacitor value is 500 pF, and polysilicon resistors are typically of 35 MΩ. Over the full silicon sensor production the average total leakage current is of 116 nA at 150 V, well below the specification of 900 nA.

To limit power consumption, electronics density and transferred data, every other strip is readout, thus one ladder provides a total of 384 readout channels. The ladders are operated with a bias voltage of 80V.

2.2. Front-end electronics and data acquisition

The Tracker Front-end Hybrid (TFH) board collects and amplifies the signals coming from the strips. Mechanically it is also an important component of the ladder, as the detectors are glued on the 380 mm-long flex extension of the board. Through the flex part, the TFH brings the bias voltage to the backside of the detectors. For redundancy two DS18S20 temperature sensors [5] are also mounted on the TFH. The board also integrates a flexible cable for the connection to the DAQ boards (figure 2).

The ASIC used for the strip signal shaping and amplification is the VA140, produced by IDEAS [6]. The VA140 is a 64 channel low-noise/low power high dynamic range charge sensitive preamplifier-shaper circuit, with simultaneous sample and hold, multiplexed analog readout, calibration facilities and internally generated biases. The VA chip family is a well-known component, already used in astroparticle physics experiments like AMS-01 and AMS-02 [7], where they have been used for the readout of the double-sided micro-strip detectors of the tracker. The power consumption of one ladder is 116 mW.

2.3. Silicon ladder assembly

The ladder assembly consists of the front-end board glued onto the four silicon detectors, initially placed on a precision alignment jig. After gluing, the position of the silicon detectors is measured with a coordinate measurement machine. A linear fit is applied to the measured positions of the detector alignment patterns. The RMS of the residual distribution is then computed, to estimate the alignment error. Figure 3 shows the average alignment error of the 192 ladders installed on the STK. Thanks to the jigs, the alignment precision is about 4 µm on average, much better than the required 40 µm .

Part of the ladder quality assurance, a 12-hour cosmic ray test is performed and the signal to noise ratio of cluster charges from minimum ionizing particle (MIP) is checked. On average the S/N is about 15, excellent for the application of the STK. All 192 ladders needed for the STK Flight Model were produced by the end of March 2015, for a total production time of three months, shared between two production sites (University of Geneva and INFN Perugia). The silicon detector quality has been preserved during all the STK assembly steps, the 192 ladder leakage current at 80V is 330 nA in average (figure 4).

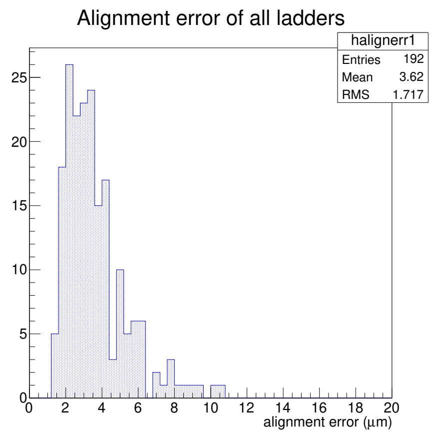

Figure 3: Alignment error of the 192 ladders mounted on the STK. The average alignment error is less than 4 µm, much better than the required 40 µm.

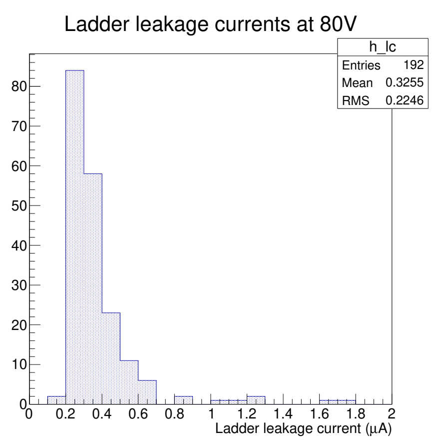

Figure 4: Total leakage current at 80V bias of the 192 ladders of the flight model STK. The average current is 330 nA, which means that the silicon detector quality has been preserved during the ladder assembly.

2.4. Plane assembly

The 192 ladders are distributed on seven support trays. Five are equipped on both sides, while the front and the rear trays are equipped only on the side facing the interior of the tracker. A layer is composed of 16 ladders, arranged in two rows of eight. A layer is thus composed of an array of 8×8 detectors, as can be seen on figure 5. On the double-sided trays, the silicon layer strips are orthogonal to each other.

A support tray is made of an aluminum honeycomb structure sandwiched between two Carbon Fibre Reinforced Polymer (CFRP) face sheets of 0.6 mm thick each (1.0 mm for trays with tungsten). It forms a light but rigid structure that can sustain the vibrations and the accelerations of a rocket launch. For the second, third and fourth trays, 1 mm thick tungsten plates are glued onto the lower CFRP sheet, inside the tray. The converter is thus located immediately above the corresponding tracking layer, to ensure good efficiency of conversion detection. The trays have been produced at Composite Design Sàrl [8]. The trays equipped with tungsten layer have been X-ray scanned at CERN, to check the alignment of the tungsten plates with respect to the four tray corners.

The ladder installation on each tracker tray has been done using an alignment and transfer jig, placed onto a precision frame holding the tray. The position of the 64 silicon sensors of the fully equipped tray were then measured with a coordinate measurement machine.

The trays have been stacked on top of each other to form the full tracker (figure 5). The silicon ladders on the bottom surface of a tracker tray and those on the top surface of the tray below form an X-Y tracking plane, the distance between the X and the Y layer of a tracking plane is $\sim$3 mm. The stack of the 7 trays forms 6 tracking planes that provide 12 measurement points (6 X and 6 Y) when a charged track traverses the STK.

The STK has a total power consumption of 90 W. The tracker cooling is ensured with a network of heat conductors. Pyrolytic graphite sheets (PGS) connect the front-end lateral sides with a horizontal copper band installed on the tray edges. Copper straps are transversely glued to thermally connect the

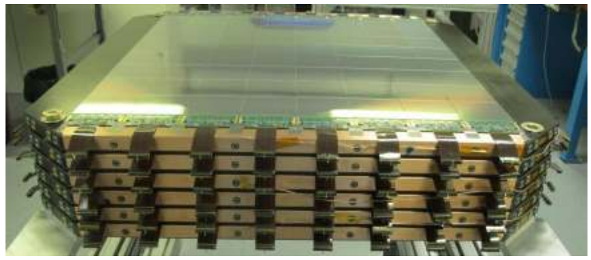

Figure 5: The STK before the assembly of the last tray. The 64 silicon detectors are visible, together with the horizontal copper bands used for the heat transfer.

trays together, and to the aluminum radiators placed on the four lateral sides of the STK. During installation on the satellite, heat pipes have then been mounted, to ensure a constant radiator temperature of 10 C.

3. Signal digitization and readout

The VA chips are separated into two independent readout groups (VAs 1 to 3, and VAs 4 to 6). Both groups are readout in parallel, but the VAs of a same group are serially readout. Thus 192 clock signals are necessary to transfer the 384 silicon strip signals. Each group has its own amplification circuit, which analogical outputs are then transferred to the main STK data acquisition boards (Tracker Readout Boards, TRB).

A TRB circuit reads out 24 ladders, and is composed of a stack of three boards. The ADC board, to which are connected the ladders, performs the analog to digital conversion of the ladder signals. The FPGA board has two FPGAs which manage the communication with the DAMPE DAQ system, and the generation of the control signals necessary for the 24 ladder readout and signal digitization. The Power board produces the voltages necessary for the front-end electronics and the TRB circuit, as well as the silicon bias voltages. To reduce the data size, the FPGAs perform a data compression, using a zero-suppression and cluster finding algorithm. Eight TRBs are needed to readout the whole STK: two TRBs are mounted side by side on each STK edge. The TRB system has been designed and produced by IHEP, Beijing.

4. Silicon detector performance studies

DAMPE will not only measure ionization by singly-charged particles but also nuclei. The study of cosmic ray propagation models are tested by examining the abundance ratios of secondary to primary particles, such as boron to carbon. For this it is necessary to record the amplitude of the signal measured at the strip level, and to precisely reconstruct the charge deposited inside the silicon detectors. Such study has to be conducted in two steps, first with particles of charge 1, then with higher charge particle. The next sections will focus on tests done with charge 1 particles.

As the strip analog signal is acquired, it is also interesting to evaluate the position resolution performance of the detector, in terms of particle track impact point and incidence angle.

For these purposes two modules have been exposed to 400 GeV proton beams at CERN. The ladders were installed in the middle of a beam telescope made of six HV-CMOS pixel detectors built by the ATLAS Geneva group, providing track resolution of ~5 µm. The module performance in terms of charge collection and spatial resolution for different angle of incidence have been studied.

4.1. Performance for 0° incident angle

A cluster finding is done on each event, after pedestal and common mode noise subtraction. A cluster is by definition a group of at least one channel having a signal larger than 4 times the channel noise, and having all neighboring channels with signal larger than 1.5 the channel noise. The cluster charge is then the sum of each individual channel signal, in ADC counts. Each channel signal, measured in ADC counts, is proportional to the electrical charge measured at the input of the VA channel. If no charge is lost inside the silicon detector, the cluster charge is proportional to the energy deposited by the traversing particle.

The typical cluster charge distribution for particles with 0° incidence is shown in figure 6. One clearly notes the double-peak structure of the distribution. This is due to the contribution of two separate distributions. The one

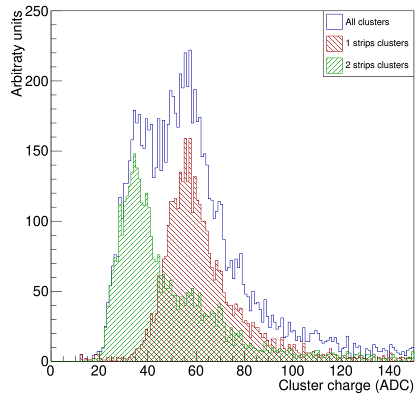

Figure 6: Signal distribution for a DAMPE silicon ladder, for charge one particles. Two distributions are clearly visible. The highest peak distribution corresponds to the contribution of the single-channel clusters, while the lowest peak distribution corresponds to the 2-channel clusters.

with largest maximum is due to the contribution of particles traversing the detector close to a readout strip. In such cases the cluster is mostly composed of a single channel. The distribution with lower maximum is the contribution from the particles traversing the detector close to floating strips, i.e. strips which are not connected to the front-end electronics, thus generating a 2-strips cluster. When the particle travels close to a floating strip, the electrical signal generated by ionization is then shared with the two neighbors connected to the front-end, through capacitive coupling. Depending on the capacitive properties of the strips between each other, and with the detector bulk, part of the charge will not reach the readout strips. In the case of the DAMPE ladders, ~ 65 % of the originally generated charge is actually measured by the neighboring readout strips, as we can see in figure 6.

Such an effect must be then taken into account when one needs to precisely measure the energy deposited by the crossing particle.

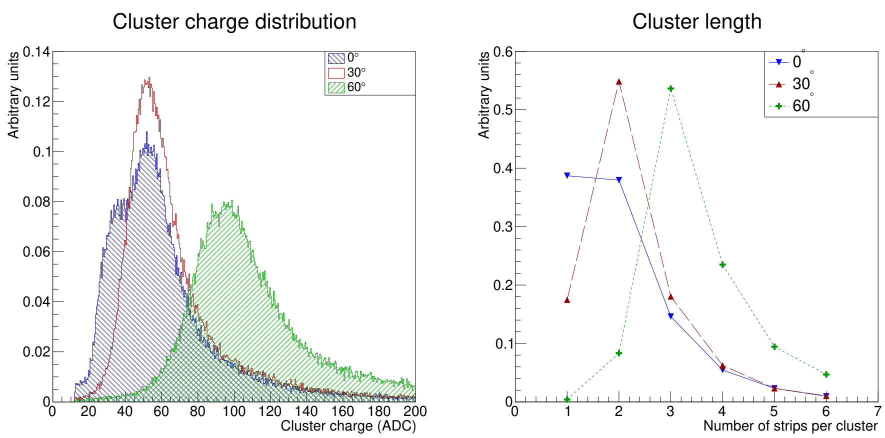

Figure 7: Cluster charge distribution (left) and cluster size (right) for incident angles 0 °, 30 ° and 60 °.

4.2. Performance for inclined tracks

In DAMPE, the maximum incidence angle acceptance of the STK is limited by the size of BGO to 60 °. It is thus interesting to study the detector behavior for inclined tracks. The rotation axis considered here is parallel to the strips, to study the cluster size change with respect to the particle incidence angle. Thanks to the high resolution beam telescope, the reconstructed tracks allows for a detailed study of the charge collected by the detector for various incidence angles. Data within a range from 0 ° to 70 °, with a step of 10 ° have been collected. The figure 7 (left) shows the cluster charge distributions for three angles of incidence (0 °, 30 ° and 60 °).

When the track is inclined, the charge collected at the level of the readout strips is the result of two contributions. In addition to the effects of the capacitive charge sharing observed for the 0 °-angle tracks (figure 6), the inclination of the track induces a charge distribution between all the strips covered by the projection of the track on the silicon plane. As an example, with an incident angle of 21 °, the projected track covers a distance equivalent to the strip pitch p of 121 µm: the charge will be shared between two neighboring strips. For the typical study angles of 30 ° and 60 °, the projected distance is equivalent to

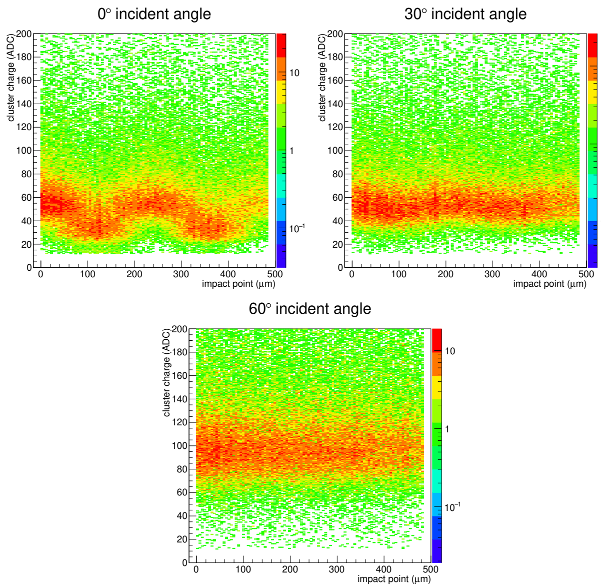

Figure 8: Measured energy as a function of the impact point, for 0 °, 30 ° and 60 ° incident angles. The effect of different charge collection behavior, visible at 0 °, is already much attenuated at 30 °.

$1.5 \cdot p$ and $4.6 \cdot p$, respectively. As an example, the cluster size for three different angles of incidence is shown in figure 7 (right). As expected, for 30 °, the charge is mainly shared between two readout strips, while the number of involved strips increases to three at 60 °.

Defining as impact point (IP) the position of the track on the silicon ladder as extrapolated by the beam telescope, we examined the cluster charge as a function of the impact point and the incident angle (figure 8). While at 0 ° one can clearly see the effect of different charge collection depending on the passage close to a readout or floating strip, this effect attenuates when the incidence angle increases, as more strips are involved in the charge detection.

5. Spatial resolution

Defining the cluster center of gravity (cog) as the weighted mean of the position of each strip, we define the residual r as: $r = IP - cog$. Figure

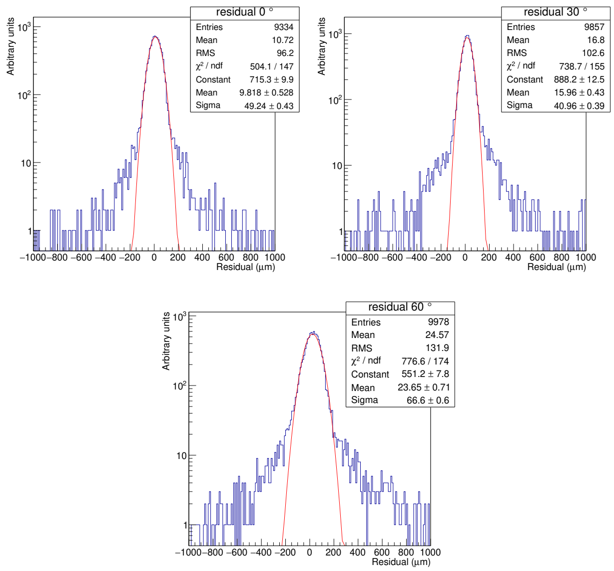

Figure 9: Residual distributions, for 0 °, 30 ° and 60 ° incident angles. The σ of the gaussian fit provides a preliminary estimation of the detector spatial resolution.

9 shows the gaussian fits of the residual distributions for incidence angles of 0 °, 30 ° and 60 °. The resolution can thus be extrapolated from the σ of the gaussian fit (the contributions due to the resolution of the beam telescope are negligible). The results shown in figure 9 are still preliminary and a detailed study of the dependence on impact point and cluster dimension is in progress. Figure 10 shows the resolution from 0 ° to 70 ° in steps of 10 °. Thanks to the analog readout, it is possible to take into account the charge sharing due to the capacitive strip coupling. The resolution is less than 50 μm for incidence angles lower than 40 °, and always much lower than the 70 μm achieved with a digital position finding algorithm [9].

6. Status of STK Flight Model

The STK Flight Model, to be used in the DAMPE payload, has been integrated in April 2015 in Geneva and tested with cosmic rays for several days, before being delivered to IHEP in Beijing. Acceptance level of vibration and

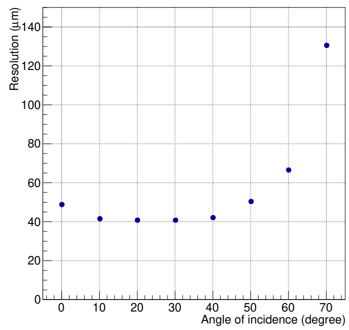

Figure 10: Spacial resolution as a function of the impact angle. Below 70 °, the resolution is much lower than the 70 μm achieved with a digital position finding algorithm.

thermal vacuum tests were conducted in Beijing in May 2015. In June 2015 the STK Flight Model has successfully passed the DAMPE payload integration test, then the DAMPE satellite integration test. In July 2015 the full DAMPE instrument has been tested in a thermal vacuum chamber. A vibration test was done in September 2015, followed by in flight simulation tests and aging tests. After 6 months of intensive manipulations and tests, the STK remains in excellent quality: as of November 2015, the number of noisy channels (noise > 5 ADC counts) is stable since the STK integration and remains below 0.5%. Only 18 ($< 0.03\%$) channels out of the 74382 need to be masked. The DAMPE satellite has been transferred to the launch site on Nov. 15th, 2015.

7. Conclusions

The Silicon-Tungsten tracker (STK) of the DAMPE mission is based on the robust technology of single-sided micro-strip detectors with analog readout. It will play a crucial role in track reconstruction, gamma-ray detection, cosmic ray charge measurement and overall particle identification. The flight model has been assembled from January to April 2015, then delivered to China, where it has successfully passed all the acceptance tests. The silicon modules are thoroughly studied, and measurements done for individual modules to calibrate the full STK. The charge collection in terms of particle impact point and angle have been presented. Thanks to the analog readout of the strips, it is possible to evaluate the incoming particle charge, as well as achieve a spacial resolution better than 50 μm, for incident angles lower than 40°.

The DAMPE satellite has been assembled during the summer 2015, and has been successfully launched on 17 December 2015.

Acknowledgement

The authors wish to express their gratitude to M. Prest and E. Vallazza of the AGILE Silicon Tracker collaboration for fruitful discussions on tracker design and for kindly allowing us to use the AGILE silicon sensor geometry. The generosity of CERN for providing beam time allocation and technical assistance at the PS and SPS beam lines, as well as general logistical support is acknowledged. This work is supported by the Chinese Academy of Sciences, the Swiss National Science Foundation and INFN, Italy.

References

[1] Science Magazine 332 (6032) 904.

[2] W. B. Atwood et al., The Astrophysical Journal 697 (2) (2009) 1071.

[3] M. Feroci et al., Nucl. Instr. and Meth. A 581 (2007) 728–754.

[4] http://www.hamamatsu.com.

[5] https://datasheets.maximintegrated.com/en/ds/DS18S20.pdf.

[6] Integrated Detector Electronics AS, http://www.ideas.no.

[7] G. Ambrosi, Nucl. Instr. and Meth. A 435 (1999) 215–223.

[8] http://www.compositedesign.ch.

[9] R. Turchetta, Nucl. Instr. and Meth. A 335 (1993) 44–58.