The CALorimetric Electron Telescope (CALET) for high-energy astroparticle physics on the International Space Station

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Status and performance of the CALorimetric Electron Telescope (CALET) on the International Space Station

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Abstract

The CALorimetric Electron Telescope (CALET) space experiment, currently under development by Japan in collaboration with Italy and the United States, will measure the flux of cosmic-ray electrons (including positrons) to 20 TeV, gamma rays to 10 TeV and nuclei with Z=1 to 40 up to 1,000 TeV during a two-year mission on the International Space Station (ISS), extendable to five years. These measurements are essential to search for dark matter signatures, investigate the mechanism of cosmic-ray acceleration and propagation in the Galaxy and discover possible astrophysical sources of high-energy electrons nearby the Earth. The instrument consists of two layers of segmented plastic scintillators for the cosmic-ray charge identification (CHD), a 3 radiation length thick tungsten-scintillating fiber imaging calorimeter (IMC) and a 27 radiation length thick lead-tungstate calorimeter (TASC). CALET has sufficient depth, imaging capabilities and excellent energy resolution to allow for a clear separation between hadrons and electrons and between charged particles and gamma rays. The instrument will be launched to the ISS within 2014 Japanese Fiscal Year (by the end of March 2015) and installed on the Japanese Experiment Module-Exposed Facility (JEM-EF). In this paper, we will review the status and main science goals of the mission and describe the instrument configuration and performance.

Keywords: electrons, calorimeter, nearby sources, dark matter, ISS

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1. Introduction

CALET (CALorimeteric Electron Telescope) [1] is a Japanese-led international mission funded by the Japanese Space Agency (JAXA), the Italian Space Agency (ASI) and NASA. The instrument is being designed and built in Japan, with hardware contributions from Italy and assistance from collaborators in Italy and the United States. It is expected that the instrument will be launched within 2014 Japanese Fiscal Year (by the end of March 2015) by a Japanese carrier, HII Transfer Vehicle (HTV), and robotically installed on the Japanese Experiment Module-Exposed Facility (JEM-EF) on the International Space Station (ISS) for a 5 year mission collecting new data on high-energy cosmic and gamma rays.

The primary science goal of CALET is to perform high-precision measurements of the electron spectrum from 1 GeV to 20 TeV in order to observe discrete sources of high-energy particle acceleration in our local region of the Galaxy. Thanks to its observations of cosmic-ray electrons and gamma rays from few GeV up to the TeV and nuclei from a few 10 GeV up to the several 100 TeV, the CALET mission will address many of the outstanding questions of High-Energy Astroparticle Physics, such as the origin of cosmic rays (CRs), the mechanism of CR acceleration and galactic propagation, the existence of dark matter and nearby CR sources. It will also monitor gamma-ray transients with a dedicated gamma-ray burst instrument and study solar modulation. Fig. 1 and Fig. 2 show CALET attachment port #9 on the JEM-EF and a schematic overview of the CALET instrument, respectively. The instrument pallet includes a Gamma-Ray Burst Monitor (CGBM), composed of a hard X-ray monitor (HXM) and a soft gamma-ray monitor (SGM), an Advanced Sky Camera (ASC) for attitude determination, a Mission Data Controller (MDC) to manage the individual detector systems and handle the accumulated data, as well as the CALET instrument itself.

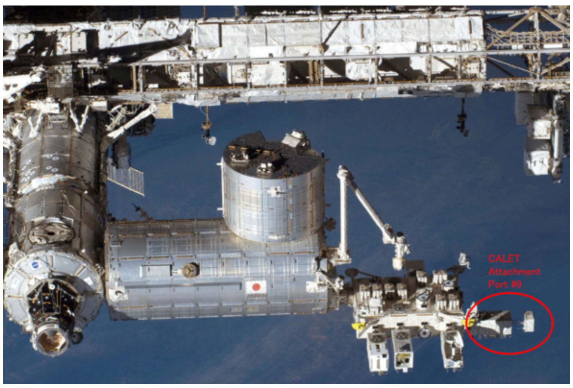

Figure 1: CALET attachment port #9 on the Japanese Experiment Module-Exposed Facility (JEM-EF).

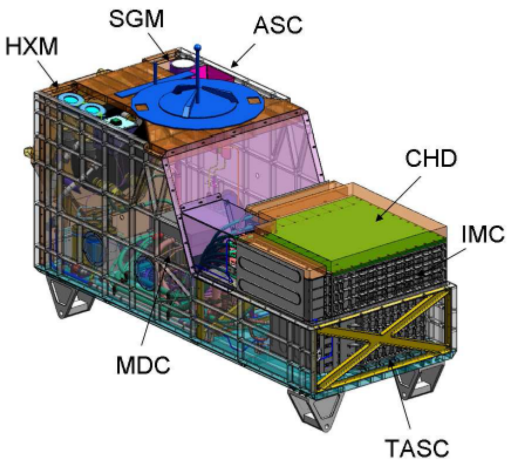

Figure 2: CALET instrument package showing the main calorimeter and CGBM subsystems.

The unique feature of CALET is its thick, fully active calorimeter that allows measurements well into the TeV energy region with excellent energy resolution, coupled with a fine imaging upper calorimeter to accurately identify the starting point of electromagnetic showers and reconstruct the incident CR and gamma-ray direction with good angular resolution. CALET instrument will thus provide an excellent separation between hadrons and electrons and between charged particles and gamma rays. These features are essential to search for possible nearby astrophysical sources of high-energy electrons and search for dark matter signatures in both the electron and gamma-ray spectra.

The hadronic data provide another channel through which the details of particle acceleration in supernova remnants or other sources will be investigated. Equipped with a charge identifier module, placed at the top of the apparatus and capable to identify the atomic number Z of the incoming cosmic rays, CALET will perform long-exposure observations of cosmic nuclei from proton to iron and will detect trans-iron elements with a dynamic range up to Z=40 [2].

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2. The CALET instrument and its performance

Heart of the mission is the main telescope, shown in detail in Fig. 3, which has a field of view of ~ 45° from the zenith. CALET is an all-calorimetric instrument, with a total thickness equivalent to 30 radiation lengths (X_0) and 1.3 proton interaction lengths (λ_I), preceded by a particle identification system. The energy measurement relies on two kinds of calorimeters: a fine grained pre-shower, known as IMaging Calorimeter (IMC), followed by a Total AbSorption Calorimeter (TASC). The effective geometrical factor of CALET for high-energy electrons is $\simeq$ 1,200 cm^{2}sr and the total weight of the system will be approximately 650 kg.

In order to identify individual chemical elements in the cosmic-ray flux, a Charge Detector (CHD) has been designed to measure the charge of the incoming nuclei via the Z^2 dependence of the specific ionization loss in a double layered, segmented, plastic scintillator array positioned above the IMC. Each layer is made of 14 plastic scintillator paddles, with dimensions 45 cm (L) × 3.2 cm (W) × 1 cm (H). This segmented configuration has been optimized to reduce multi-hits on each paddle caused by backscattering particles. The two layers of paddles are orthogonally arranged to determine the incident position of the cosmic rays. Scintillation light from each paddle is collected and readout by a photomultiplier tube (PMT). The CHD and related front-end electronics have been designed to provide incident particle identification over a large dynamic range for charges from Z=1 to Z=40. Charge identification capabilities of CHD have been measured by exposing it on an ion beam at GSI facility [3] and CERN Super Proton Synchrotron (SPS), giving a charge resolution ranging from 0.15 electron charge units (e) for B to $\simeq$ 0.30-0.35 e in the Fe region.

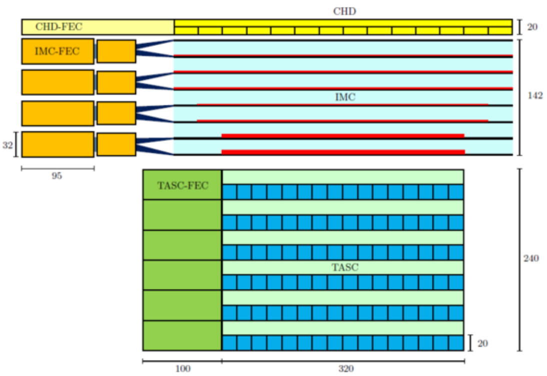

Figure 3: CALET instrument schematic side view. Dimensions are in mm.

The IMC will image the early shower profile with a fine granularity by using 1 mm^2 scintillating fibers (SciFi) individually read out by Multi-Anode PhotoMultipliers Tubes (MAPMTs). The imaging pre-shower consists of 7 layers of tungsten plates, each separated by 2 layers of 1 mm^2 scintillating fibers, with square cross section, arranged in belts along the X and Y directions, and is capped by an additional X,Y SciFi layer pair. Each SciFi belt is assembled with 448 fibers and the dimensions of the SciFi layers are 44.8 cm (L) × 44.8 cm (W) × 0.2 cm (H). The total thickness of the IMC is equivalent to 3 X_0. The first 5 tungsten-SciFi layers sample the shower every 0.2 X_0 while the last 2 layers provide 1.0 X_0 sampling. The IMC fine granularity allows to: (i) reconstruct the incident particle trajectory; (ii) determine the starting point of the shower; (iii) separate the incident from backscattered particles. Above several tens of GeV, the expected angular resolution for photons is ~ 0.24°, while the angular resolution for electrons is ~ 0.13°, which is better than that of gamma rays. The readout of the SciFi layers consists of 64-anode Hamamatsu R7600-M64 photomultiplier tubes (MAPMTs).

The homogeneous calorimeter is designed to measure the total energy of the incident particle and discriminate electromagnetic from hadronic showers. TASC is composed of 12 layers, each comprised of 16 lead tungstate (PWO) logs. Each log has dimensions of 326 mm (L) × 19 mm (W) × 20 mm (H). Layers are alternately arranged with the logs oriented along orthogonal directions to provide a 3D reconstruction of the showers. Six layers image the XZ view and 6 the YZ view. The total area of the TASC is about 1,063 cm^2 and the total thickness corresponds to about 27 X_0 and 1.2 λ_I at normal incidence. Each PWO log in the upper layer (16 bars) is readout by a PMT to generate a trigger signal. Hybrid packages of silicon Avalanche PhotoDiode and silicon PhotoDiode (Dual APD/PD) are used to collect light from the remaining PWO bars. The readout system of each pair of APD/PD sensors is based on Charge Sensitive Amplifier (CSA) and pulse shaping amplifier with dual gain. Such a readout system provides a dynamic range covering 6 orders of magnitude and allows to measure in each bar signals spanning from 0.5 MIPs (Minimum Ionizing Particles) to 10^6 MIPs, which is the energy deposit expected from a 1,000 TeV shower.

The main scientific objective of CALET is the measurement of the electron spectrum over the range from 1 GeV to 20 TeV. For this purpose, TASC is required to have a linear energy response from GeV up to the TeV region and an excellent resolution to resolve possible spectral features as expected in case of the presence of nearby CR sources or dark matter. According to

Monte Carlo simulations and beam test data, TASC can measure the energy of the incident electrons and gamma rays with resolution ~ 2% above 100 GeV. Another necessary requirement is to efficiently identify high-energy electrons among the overwhelming background of CR protons. Particle identification information from both IMC and TASC is used to achieve an electron detection efficiency above 80% and a proton rejection power ~ 10^5.

In the region above 10 GeV, electrons and gamma rays are separated by the IMC, as gamma rays have no tracks in the IMC, except for backscattered particles. Furthermore, the charge measurements of the CHD can be used to reject photons. A gamma-ray rejection power (for electron observations) is expected to be larger than 500, while the electron rejection power (for gamma-ray observations) is larger than 10^5.

Charged particles and gamma rays with energy larger than 10 GeV will be triggered above a 15 MIP threshold from the sum of the signals from the last two IMC SciFi belts and a 55 MIP threshold from the signal of the top layer in the TASC. Electrons in the energy range between 1 GeV and 10 GeV will be observed only for a limited exposure by reducing the IMC trigger threshold. The trigger rate above 10 GeV is estimated around 13 Hz.

3. CALET science goals

It has become increasingly clear in recent years that major changes in, and the evolution of, our own and other galaxies are intrinsically linked to high-energy phenomena – e.g. Supernova explosion, Black Hole accretion, Active Galactic Nuclei (AGN) jets, etc. – and that these involve the acceleration of charged particles, often to extreme energies. The release of these high-energy particles fuels the galactic cosmic radiation, while the interactions of the energetic particles produce X-ray and gamma radiation through synchrotron, inverse Compton and pion decay processes. CALET will provide another important window on the High-Energy Universe by observing high-energy electrons, hadrons, diffuse gamma rays up to the highest energies observed in space.

3.1. Search for nearby sources of high-energy electrons

It is generally accepted that CRs are accelerated in shock waves of supernova remnants (SNRs), which are the only galactic candidates known with sufficient energy output to sustain the CR flux. Recent observations of electron synchrotron and gamma-ray emission from SNRs proved that high-energy charged particles are accelerated in SNR shocks up to energies beyond 100 TeV [4]. Unlike the hadronic component of CRs, the electrons, during their diffusion in the Galaxy, suffer from radiative energy losses proportional to their squared energy. Thus TeV electrons observed at Earth likely originated in sources younger than 10^5 years and < 1 kpc far from the Solar System. Since the number of such nearby SNRs is limited (e.g.: Vela, Monogem, Cygnus Loop remnants, and few others), the electron energy spectrum around 1 TeV could exhibit spectral features and, at very high energies, a significant anisotropy in the electron arrival directions would be expected [5]. Thanks to its excellent energy resolution and capability to discriminate electrons from hadrons, CALET will be able to investigate possible spectral structures by detecting very high-energy electrons and possibly provide the first experimental evidence of the presence of a nearby CR source.

For a given choice of model parameters as calculated by [5], Fig. 4 shows a simulated electron spectrum (dotted line) and the anticipated data points from a five year CALET mission compared to a compilation of previous electron measurements. Moreover, a significant anisotropy ~ 10% in the electron arrival directions is expected for Vela. The investigation of possible spectral features in the electron (and positron) spectrum and the observation of a possible anisotropy in the direction of the Vela SNR are one of the main goals of CALET.

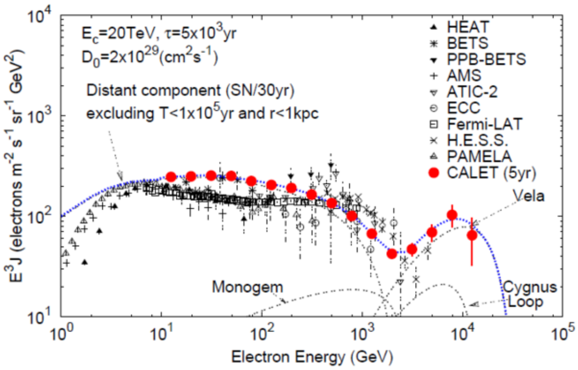

Figure 4: Simulated electron spectrum from a SNR scenario model as in [5] (dotted line) and the predicted data points from a five year CALET mission compared to previous electron spectra.

3.2. Measurements of primary and secondary nuclei

A direct measurement of the high-energy spectra of individual cosmic-ray nuclei up to the PeV scale provide important complementary information to the one

derived from electron observations. Possible charge-dependent high-energy spectral cutoffs, hypothesized to explain the CR “knee” [6], or spectral hardening due to non-linear acceleration mechanisms [7], could only be investigated by a space experiment with long enough exposure to extend the direct measurement of CR nuclei spectra to unprecedented energies.
CALET will be able to identify CR nuclei with individual element resolution and measure their energies in the range from a few tens of GeV to several hundreds of TeV. In five years of data taking on the ISS, it is expected to extend the proton energy spectrum up to ~ 900 TeV, the He spectrum up to 400 TeV/amu (Fig. 5) and measure the energy spectra of the most abundant heavy primary nuclei C, O, Ne, Mg, Si and Fe with sufficient statistical precision up to ~ 20 TeV/amu. It will also investigate precisely possible spectral features or deviations from a pure power-law spectrum, as observed by PAMELA for proton and helium spectra [8].

Additional information on the CR propagation

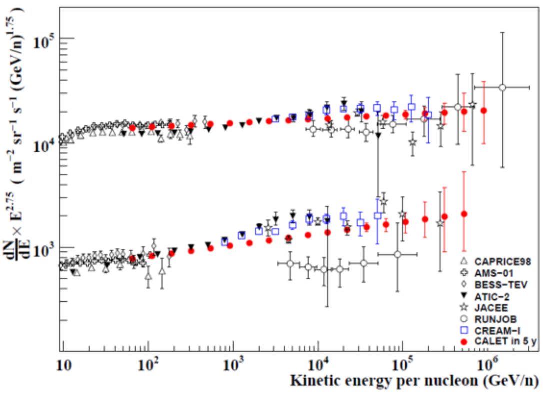

Figure 5: Expected CALET measurement of the proton and helium energy spectra after a five year observation, compared to previous data.

mechanisms might be obtained by directly measuring, besides proton and helium energy spectra, the secondary-to-primary flux ratios. Direct measurements of the secondary-to-primary flux ratios - most notably Boron/Carbon - can discriminate, via its energy dependence, among different propagation models. This observable is less prone to systematic errors than absolute flux measurements. The relative abundances of CR secondary-to-primary elements (like B/C or sub-Fe/Fe) are known to decrease, following a power law in energy $E^{-\delta}$, where δ is a key parameter in the description of the CR diffusion in the Galaxy at high energies. Unfortunately, the available measurements, pushed to the highest energies with Long Duration Balloon experiments, suffer from statistical limitations and large systematic errors at several TeV/n, due to the residual atmospheric overburden at balloon altitude. This sets an effective limit to the highest energy points of the secondary-to-primary ratios obtainable with measurements on balloons and has not allowed so far to place a stringent experimental constraint on the value of δ. On the other hand, experiments in space are free from this limitation. Taking advantage of its long exposure in space and the absence of atmosphere, the CALET mission will provide new data to improve the accuracy of the present measurements above 100 GeV/n and extend them above 1 TeV/n, as illustrated in Fig. 6 [9].

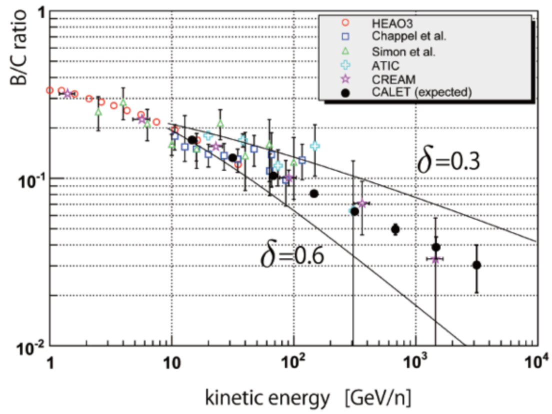

Figure 6: Expected B/C ratio for five year observations with CALET compared to the observed data.

3.3. Detection of trans-iron elements

According to the results of a dedicated beam test with relativistic ions [10, 3], the capability of the CHD to provide charge separation can be extended to heavy nuclei above nickel (Z=28). A dedicated study [11] of the expected fluxes along the ISS orbits indicates that in the 30 < Z < 40 charge range CALET should collect 4-5 times the ultra-heavy nuclei statistics of TIGER [12]. The advantage of CALET is that the measurements will be less sensitive to systematic effects since there will be smaller corrections for nuclear interactions from the residual atmosphere at balloon altitude. In the 40 ≤ Z ≤ 46 charge range CALET can make exploratory measurements with statistical precision of ~ 25-30% for even-Z nuclei to the highest charge resolved by the dynamic range of the instrument.

3.4. Dark matter search

Besides studying the CR sources and diffusion, CALET will also conduct a sensitive search for signatures of dark matter candidates in both the electron plus positron (1 GeV - 20 TeV) and gamma-ray (10 GeV - 10 TeV) spectra. Survivor dark matter candidates (i.e. not yet excluded by the available experimental findings and current theoretical work) include Weakly Interacting Massive Particles (WIMPs) and exotic states like Kaluza-Klein (KK) particles, the latter resulting from theories involving compactified extradimensions. Neutralinos are expected to annihilate and produce gamma rays and positrons as a signature. The predicted signatures are dependent on models with many parameters and even a non-observation by CALET will effectively constrain these parameters or eliminate some theories. Like neutralinos, KK particles can annihilate in the galactic halo and produce an excess of both positrons and electrons that may be observable at Earth. Unlike neutralinos, however, direct annihilation of KK particles into e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ is not chirality suppressed and, consequently, the KK electron signal is enhanced relative to that from neutralinos. Also, since this is a direct annihilation, it results in the appearance of monoenergetic electrons and positrons which would create a discrete spectral feature (a sharp edge) in the cosmic $e^+ + e^-$ spectrum at an energy equal to the particle's mass.

The prominent increase of the positron fraction over 10 GeV, reported by PAMELA [13], Fermi-LAT [14] and AMS-02 [15], has fueled an intense debate whether this observation is related to dark matter or it is the result of an astrophysical effect. With its excellent energy resolution, hadron rejection power and long exposure in space, CALET will shed new light on this open question. Although the CALET telescope cannot separate the sign of charge, it has a potential to detect the distinctive features from dark matter annihilation in the electron and positron energy spectrum, as can be seen in Fig. 7 [9].

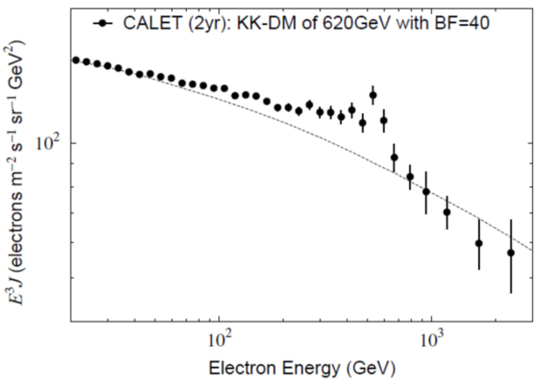

Figure 7: Simulated energy spectrum of $e^+ + e^-$ from Kaluza-Klein dark matter annihilation with a 620 GeV mass for two year observations with CALET.

If neutralinos are the dark matter particles, they might be seen as a line in the high-energy gamma-ray spectrum. Recent hints of a spectral line from the galactic center at ~ 135 GeV come from Fermi-LAT data [16]. Since CALET has an outstanding energy resolution (~ 2% over 100 GeV), it is an ideal detector to observe monochromatic gamma rays from dark matter annihilations from several tens of GeV up to several tens of TeV, as shown in Fig. 8 [9].

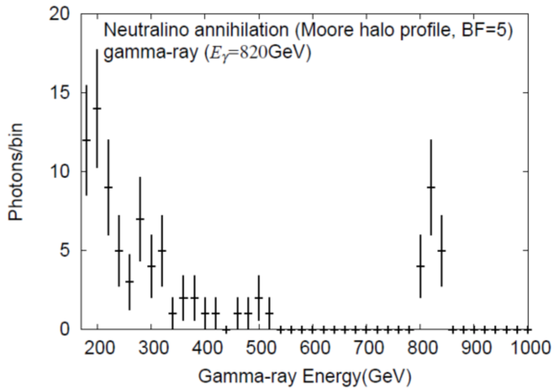

Figure 8: Simulated energy spectrum of a gamma-ray line at 820 GeV from neutralino annihilation towards the galactic center including the galactic diffuse background for two year observations with CALET.

4. CALET beam tests

CALET development began in March 2010 after it was approved by JAXA as an experiment utilizing the JEM-EF on the ISS. Bread Board Models (BBM) were first made tentatively for electronics and detector structures. Front-end circuits (FEC) of limited channels for the IMC and TASC were made as BBM to verify electronics design.

As for detector structures of the IMC and TASC, one fourth of them was also made as BBM to establish assembling methods of detectors and to perform vibration tests. After considering results obtained from BBM, Structure Thermal Models (STM) of the CHD/IMC and TASC were made to verify design of structure and temperature in view of material, mass, heat, strength, and so on.

After various tests with BBM and STM, a Proto-Flight Model (PFM) of CALET which will become a Flight Model (FM) has been developed since 2012. After Acceptance Tests of the PFM to verify its overall functions and performance, it will be launched as the CALET FM.

4.1. Prototype tests in 2010 and 2011

After CALET was approved as an experiment on the the ISS JEM-EF in 2010, its configuration was almost fixed. Therefore, beam tests with CALET prototypes were carried out in 2010 and 2011.

The CALET prototype I developed in 2010 had a limited lateral width (perpendicular direction to beams) and only one (X) direction, while it had a full depth (parallel direction to beams) of the IMC and two third depth of the TASC.

In 2011, the CALET prototype I for beam tests was improved by increasing the number of PWO crystals of the TASC and replacing some parts of the FEC with test circuits for the CALET FM. The longitudinal structure of the CALET prototype II (Fig. 9) was similar to that of the CALET FM, while the lateral size was reduced. The CHD was composed of 4 plastic scintillator paddles of dimensions 45.0 cm (L) × 3.0 cm (W) × 1.0 cm (H). The IMC was equipped with 8 layers of SciFi belts, each composed of 32 fibers (arranged only along one axis). The total thickness of the 7 tungsten plates was equivalent to ∼ 3 X_0. The TASC had 12 layers, each consisting of only 3 PWO logs that were arranged along one axis. The total thickness of the TASC was ∼ 27 X_0. Signals of each SciFi belt were detected by 64-channel MAPMTs. To readout the PWO signals, two PMTs were used for the top layer and an APD and a PD were attached to each crystal in the remaining layers.

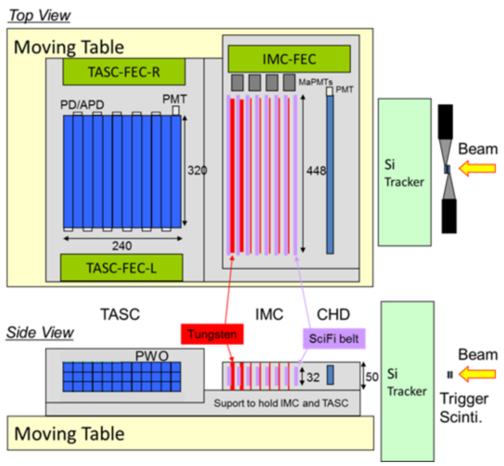

Figure 9: Configuration of the CALET prototype II for the beam test at CERN-SPS in 2011.

The beam tests were carried out at the H4 beam line in the north area of the CERN-SPS for one week both in 2010 and 2011. Positron and proton beams were used in the energy region from 10 to 290 GeV and from 10 to 350 GeV respectively, and 150 GeV muon beams for calibration. The detector surface was scanned with the particle beams by moving horizontally and vertically the mechanical table on which it was placed. During test about 2.3×10^5 muon, 3.8×10^5 electron and positron and 1.9×10^6 proton events were collected.

4.2. Beam Test Model test in 2012

In 2012, the CALET BBM of electronics and STM of the CHD/IMC and TASC were available for a beam test because the development and manufacturing of the PFM had already started at that time. Therefore, a CALET Beam Test Model (BTM), as shown in Fig. 10, was assembled for the 2012 beam test by making use of BBM and STM. The CHD-STM structure comprised of

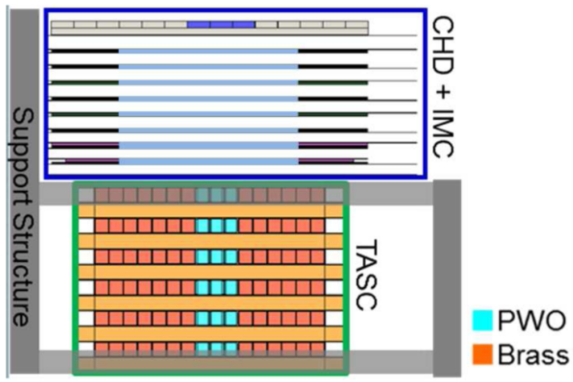

Figure 10: Configuration of the CALET BTM for the beam test at CERN-SPS in 2012.

6 plastic scintillator bars, 3 in each layer (X and Y), to which the PMTs were attached through light guides, and 22 dummy plastic bars without PMTs. The IMC-STM structure contained 4096 scintillating fibers. The central 256 out of 448 scintillating fibers in one layer were used for the beam test and 64 MAPMTs in total were attached to read out all the scintillating fibers. The TASC-STM structure was composed of 36 PWO crystals, 3 in each layer, into slots of the central PWO holder made of CFRP (Carbon Fiber Reinforced Plastic). PMTs were attached to the 3 PWO crystals in the top layer and 33 sets of APD/PD were attached to the other PWO crystals. Brass bars made as mass dummies for STM tests were put into the other 156 slots.

Beam test at CERN-SPS lasted 3 weeks in 2012 because CALET has been approved as a recognized experiment (RE-25) since February 2012. One machine time was assigned to ion beam tests at H8 for 2 weeks and the other was continuously assigned to electron/proton beam tests at H4 for one week. About 1.9 million electron events at energies from 10 to 290 GeV and 3.5

million proton events from 30 to 400 GeV were totally gathered at H4 and H8 beam lines. Unfortunately, all ion runs at the SPS were postponed and electron/proton beam tests were also carried out at H8. Beam time was therefore requested at the H8 beam line for an ion run in 2013 before the accelerator facility of CERN was closed for more than one year.

4.3. Charge Detector test in 2013

During beam test at SPS in January 2013, the readout of 2 plastic scintillator bars of the CHD with the BBM TASC-PMT-FEC, which was common for the readout of the CHD-PMT and TASC-PMT, was tested. Relativistic ions were extracted as secondary products from the interactions of a primary Pb beam of the SPS impinging on an internal Be target. Fully ionized nuclear fragments with A/Z=2, ranging from deuterium to heavy nuclei with atomic number $Z > 26$, were steered along the H8 beam line of the SPS. The different fragment species were selected through the silicon detector placed in front of the CHD scintillator bars. More than 15 million triggers were collected in two sets of runs with beam energies of 13 and 30 GeV/amu, respectively. The 2013 beam test at CERN confirmed the results obtained in the previous beam tests at GSI in Darmstadt [3] with a lower energy (1.3 GeV/amu) and at HIMAC in Japan [10]. Results from measurements of relativistic fully ionized nuclear fragments ($1 \leq Z \leq 33$) confirmed an expected charge resolution close to 0.15 e for light nuclei, like B and C, while reaching an almost constant value of 0.30-0.35 e in the region of Iron.

5. Summary and future prospects

The CALET mission will perform observations of very high-energy electrons, gamma rays, proton, helium and heavy ions. Nearby sources of electrons can be identified by observing the energy spectrum and the anisotropy in the TeV region. Signatures of dark matter candidates will be searched in both the electron (1 GeV - 20 TeV) and gamma-ray (10 GeV - 10 TeV) spectra. Long exposure observations of cosmic nuclei might shed light on the acceleration and transport mechanism of cosmic rays in the Galaxy and possibly unveil the origin of the cosmic-ray "knee". Beam tests from 2010 to 2013 provided a lot of data needed to develop the CALET flight hardware and confirm the validity of Monte Carlo simulations at beam energies.

CALET is anticipated to begin operations on the ISS-JEM within 2014 Japanese Fiscal Year (by the end of March 2015) with a two-year mission life, extendable to five.

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