Technical Proposal for the CERN LHCf Experiment

Measurement of Photons and Neutral Pions in the Very Forward Region of LHC


(The LHCf collaboration)

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1. Research Purpose

Knowledge of the energy distribution of particles emitted in the very forward region is critically important for the understanding of cosmic ray phenomena. So far only one experiment has obtained data in the energy region exceeding $10^{14}$ eV; the experiment that has been done by the CERN UA7 collaboration at $2 \times 10^{14}$ eV. They observed the energy distribution of photons and neutral pions in the rapidity range of $y=5-7$ [1].

A very interesting result has been reported by the AGASA cosmic ray experiment [2] that observed a considerable number of gigantic air showers in the energy region beyond $10^{20}$ eV as shown by the blue triangles of Fig. 1. It is difficult to confine cosmic rays in our Galaxy when the primary energy exceeds $4 \times 10^{19}$ eV, even when a symmetrical magnetic field of 3 micro Gauss is assumed to fill the halo. Within the present scheme of physics it is very hard to conceive of the source or the origin of such high-energy particles, especially by a bottom-up scenario. Extragalactic protons of this extreme energy are not expected to arrive at the Earth due to photo-nuclear interactions with 2.7K photons by the 3-3 resonance interaction process (formation of $\Delta(1232)$ baryons). This is called the Greisen-Zatsepin-Kuzumin (GZK) cut-off. It is also difficult for extreme energy extragalactic particles other than protons to reach the Earth. Therefore, the existence of the events above the GZK cut-off (super GZK events) must be explained by a top-down scenario such as the decay of cosmic strings, $Z_0$ burst, etc. [3] or by some yet unknown scenario. Within top down scenarios, the hypothesis that Lorentz invariance might be violated under the bottom-up scenario is involved [4]. Because of this situation it seems that a detailed study of super GZK cosmic rays may lead to a break-through in the field of fundamental particle physics and astrophysics. On the other hand the Hi Res experimental group of Utah has reported a cosmic ray energy spectrum that is consistent with the GZK cut-off [5] (the red points of Fig. 1).

At present, we cannot draw a definite conclusion on which result is correct. In view of this fact, new air shower projects – Auger [6] and TA [7] – are under way and the EUSO project is under consideration [8]. These groups use quite different experimental methods, each of which has advantages and drawbacks. Many of the experimental procedures for deriving the energy spectrum depend strongly on the model of nuclear interactions that is used in Monte Carlo simulations of the air showers. Therefore, in order to calibrate the nuclear interaction models in the
Monte Carlo codes, we think it is very important to establish the energy spectrum of particles emitted in the very forward region (which is effective for air shower development) at a much higher nuclear interaction energy region than the UA7 case. The laboratory equivalent energy of LHC is $10^{17}$ eV, therefore the calibration of Monte Carlo codes at such high energy will give a firm base to explore the GZK problem. This is discussed in more detail in Section 4 of this proposal which deals with Monte Carlo calculations.

Here we must mention another important puzzle that present experiments cannot resolve and that is whether the cosmic ray composition or the nuclear interaction cross section changes at high energy. Cosmic rays are not purely protons but they also contain the nuclei of helium, carbon, and iron. When heavy nuclei enter the top of the atmosphere, they disintegrate quickly and nuclear cascade showers develop rapidly in comparison with the showers produced by protons. Not being able to identify the primary nucleon leads to confusion over whether the primary composition or the nuclear interaction cross section is changing with energy.

The situation is presented in Fig. 2.[9] If we use the Monte Carlo QGSJET 01 model, the composition of cosmic rays at $2 \times 10^{18}$ eV must be dominated by protons. However if we use Monte Carlo DPMJET2.5 model, it is concluded that the composition of cosmic rays is a mixture of several nuclei – protons, helium, carbon and iron – and the composition does not change over a wide energy range. The experimental results of LHCf will be able to provide the production spectrum of secondary particles in the very forward region, and with this fixed data set the Monte Carlo codes can determine the composition of cosmic rays. Thus the proposed experiment is important not only to fix the cross sections in the different Monte Carlo codes but also to understand the composition of cosmic rays which cannot be determined by direct observations.

We propose to install two small imaging calorimeters (one with scintillating fibers, the other with silicon sensors) at a forward location 140m from the colliding beam intersection, for example, at the LHCb, ATLAS or CMS intersection regions. The final intersection that is chosen will be determined after discussions with the LHC machine people. With our imaging calorimeter we will be able to identify photons, measure the photon energy spectrum ($>100$ GeV), measure the photon incident position and construct the two-photon invariant mass distribution that shows a clear peak at the neutral pion mass.

After sending a Letter of Intent to the LHCC on 4 May 2004, a few new data points have been collected in the energy range around the GZK cut-off. The Auger
collaboration has published the first result of their experiment at the 29th International Conference on Cosmic Rays in Pune, India, Aug 3–10 2005 (Fig. 3). These initial results show that the cosmic ray spectrum continues to the highest energy range [10] however the statistical and systematic errors are for the moment too limited to reconcile the existence of cosmic rays beyond the GZK cut–off reported by AGASA. On the other hand the Hi Res group has presented a set of data obtained by the stereoscopic detection of extreme high energy showers and the data are consistent with the idea of the GZK cut–off (Fig. 4).

2. Experimental Method

We propose to install two small electromagnetic shower calorimeters in the forward direction 140m from the interaction point and symmetrically with respect to it. At this location, the beam vacuum chamber makes a transition from a single large diameter beam pipe to two small beam pipes joining to the arcs of the LHC as shown in Fig. 5. This “Y–vacuum chamber” is imbedded in a massive absorber (TAN) (Figs. 6 and 7) that protects superconducting magnets from IP collision debris.[11] In the crotch of the Y there is a slot with dimensions 96mm in width, 607mm in height and 1000mm in length. The slot extends from 67mm below the beam height to the top of the TAN shielding. In the absence of detectors this slot is nominally occupied by ten copper absorber bars, each 94mm in width, 605mm in height and 99mm in length. The Y vacuum chamber in front of the slot has been carefully machined to have 1r.l. projected thickness in a 100mm x 100mm square in order to avoid an undesirable correlation of detector signals with the transverse position of incident particles.

At present the LHC luminosity monitor [12] is designed to occupy the position of the fourth copper bar and the LHCf calorimeter is designed to occupy the position of the first three copper bars (Fig. 8). The vertical position of the calorimeter is designed to be remotely adjusted. When beam–beam collisions are not present, the calorimeter will be retracted 190mm above the beam height and shielded from low energy background particles by 300mm of iron and 450mm of marble which are part of the TAN structure. Two calorimeters will be prepared, and they will be installed symmetrically with respect to the interaction region. The two calorimeters are similar, but not identical. To distinguish between them in the following description we will refer them to as ‘Detector #1’ and ‘Detector #2’.
Description of Detector #1

Detector #1 is composed of 3 individual calorimeters arranged in a tower structure as shown in Fig. 9, with each calorimeter having the dimensions of 2cm x 2cm x 28cm, 3cm x 3cm x 28cm and 4cm x 4cm x 28cm respectively. The tower calorimeters are composed of tungsten plates, each plate having a thickness of 2 radiation length (r.l.) to 4 r.l.. The total thickness of each calorimeter is 54 r.l. including 1r.l. for the projected thickness of the Cu beam pipe. This absorber length is sufficient to accurately measure the photon energy up to few TeV (see Fig. 10). The space above the detector is open so that the detector can be installed from above and its vertical position adjusted by a machine that is remotely controlled, similar to a Roman pot. To identify the position of a single photon or to resolve the positions of multiple photons, x and y detectors are prepared, each of which consists of an array of 1 mm x 1 mm square scintillating fibers (SciFi). Signals from SciFi are read out by using multi-anode (=64) photomultipliers (MAPMT), Hamamatsu H7546. The quantum efficiency of H7546 photomultipliers is about 20% at the wavelength of photons emitted in SciFi. The SciFi detectors are installed at depths of 8, 10, and 38 r.l.. The two layers at 8 and 10 r.l. are used for the identification of the position of showers and the layer located at 38 r.l. is used for the identification of the shower center of nuclear cascade showers. The total number of fibers will be 512 and will require 8 MAPMTs.

Thin plastic scintillator plates (0.3 cm) will also be installed at every 2-4 r.l. for triggering and for measuring the total deposited energy. The trigger signal will be derived by using these plate scintillators within a 100ns delay time after arrival of shower signal.

Description of Detector #2

The structure of Detector #2 is similar to the one described for Detector #1, with some differences in the geometrical setup and in the position sensitive layers. It is composed of 3 calorimetric towers, 2x2 cm², 3x3 cm² and 4x4 cm², positioned as shown in Fig. 11. Each tower, 29 cm long, has the same longitudinal structure already described. However, the SciFi layers are replaced by layers of silicon micro-strips. In particular we will install 4 double layers of silicon detectors; the first one is located in front of the towers, to identify the charged particles hitting the detector; the others are placed inside the calorimetric towers, at a depth of 8, 10 and 38 r.l..
Each double layer of silicon sensors is in turn composed of a layer used to measure the x coordinates of the particles in the shower (with vertical strips) and by a layer used to measure the y coordinate (with horizontal strips). The x and y layers cover a region 12.8 x 6.4 cm$^2$, and are realized by means of 2 square sensors (6.4 x 6.4 cm$^2$), 285 µm thick, with 80 µm pitch strips.

We will use dedicated kapton fan-outs on both x and y layers in order to have the possibility of separately reading out the strips of each sensor; in this way the increased granularity of our detector will allow us to clean up the event sample, clearly separating the position measurement of the showers produced in the top tower from the ones produced in the other two towers.

The hybrid circuits and the preamplifiers will be located just above the calorimeter, where there is enough space available. In order to reduce the total number of readout channels, we will read out only every other strip. In this way the total number of readout strips amount to 6144. The front-end and readout electronics of the silicon system will be described in detail in Section 7.2.

**Calibration and readout of plastic scintillator**

The signal of the plastic scintillators will be read out by small photomultipliers such as Hamamatsu R7400U which have quantum efficiencies of 21%. The photomultipliers have a dynamic range of 10$^5$, and pulse height will be measured by using the standard VME ADCs. In actual operation, after calibration of the deposited energy by single minimum ionizing particles (MIPs), the high voltage for the photomultipliers will be reduced so they will be sensitive over a range of ionizing particle flux from 500 to 50,000 MIPs in each section of the calorimeter, except the first layer of the calorimeter. The gain of the photomultiplier of the first layer will be set to have a dynamic range of 20 to 1,000 MIPs.

In a forthcoming laboratory experiment at a CERN beam line, the calorimeter will be exposed to a muon beam and a high energy electron beam to calibrate the pulse height from the scintillators. When the calorimeter is exposed to the muon beam (single MIP), a high voltage of 1kV will be applied to the photomultipliers. At the same time, all photomultipliers will be exposed to a laser beam and the laser intensity adjusted to produce a signal equivalent to a single MIP. The laser intensity will then be increased by factors of 100, 1000, 10,000 and 100,000 times and the gain of each photomultiplier calibrated over the full dynamic range of interest. In these cases the
high voltage of the photomultipliers will be reduced to approximately 350V. The
calorimeter will then be exposed to an electron beam with energy up to 250 GeV.
Making use of the muon beam and laser calibration the number of MIPS deposited in
each layer of the calorimeter by the electron induced em shower will be compared with
the number of MIPS predicted by the EGS4 code. Thus we can make independent
check of the calibration for shower particles. In this way the photomultipliers will be
calibrated in excess of 50,000 MIPs in the plastic scintillator without saturation, which
corresponds to the shower maximum created by 7TeV electrons.

3. Beam Conditions and Integration Time

The first operation of LHC in colliding beam mode is envisioned with zero crossing
angle and with 43 equally spaced bunches per beam (~2microsec between
bunches).[12,13] The LHCf is being designed to be compatible with this early mode
of LHC operation. Specifically, the sample and hold time of the data acquisition
electronics is 2 microsec so events from adjacent bunches will not cause pileup.

To properly measure production cross sections it is necessary to operate with
luminosity low enough that the probability of more than one event per bunch crossing
is a small number. Specifically, requiring the probability of 2 or more events per bunch
crossing to be less than 1% specifies the luminosity per colliding bunch pair to be
\(~2 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1}\) or less (80mb cross section assumed. With 43 colliding bunch pairs the
total luminosity would be \(0.8 \times 10^{29} \text{cm}^{-2}\text{s}^{-1}\) or less. ). As we will see below operating
with luminosity more than two orders of magnitude less than this still assures an
adequate event rate for LHCf. The desired beam parameters for LHCf operation are
summarized in Table 3.1. For specified luminosity the bunch intensity depends on
the value of \(\beta^*\) at the collision point. Bunch intensities are given for two values of \(\beta^*\)
that have been mentioned for early LHC physics operation (18m and 1m respectively).

At the beginning of LHC colliding beam operation we would have the LHCf
calorimeter installed with the nominal vertical position of the colliding beams in the
range of the tower calorimeters and search for the beam center. If everything
performs correctly this would be done in a few minutes, even at luminosity as low as
\(10^{28}\text{cm}^{-2}\text{s}^{-1}\). The procedure would likely be repeated several times with the LHCf in
different vertical positions. We would then fix the position of LHCf and take data
until the mass of the neutral pion is cleanly observed in the two photon invariant mass
distribution. According to our Monte Carlo calculations this would take
approximately 15 minutes at luminosity $10^{28}\text{cm}^2\text{s}^{-1}$. Altogether we would need perhaps a few hours of data taking time to record the photon energy spectrum at several different vertical positions of the tower calorimeters. Factoring in the need to carefully look at the quality of the data and possibly make some adjustments we estimate a few days of running would be sufficient to obtain high quality data.

Table 3.1: Summary of beam conditions for LHCf.

<table>
<thead>
<tr>
<th>Beam parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunches per beam</td>
<td>43</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>0</td>
</tr>
<tr>
<td>Bunch separation[microsec]</td>
<td>2</td>
</tr>
<tr>
<td>Luminosity per bunch[cm$^{-2}$s$^{-1}$]</td>
<td>$&lt;2\times10^{28}$</td>
</tr>
<tr>
<td>Luminosity[cm$^{-2}$s$^{-1}$]</td>
<td>$&lt;0.8\times10^{30}$</td>
</tr>
<tr>
<td>Bunch intensity ($\beta*=18m$)</td>
<td>$&lt;4\times10^{10}$</td>
</tr>
<tr>
<td>Bunch intensity ($\beta*=1m$)</td>
<td>$&lt;1\times10^{10}$</td>
</tr>
</tbody>
</table>

4. Some results from Monte Carlo Calculations

--- 4.1 Scientific Results Expected ---

In this section, we introduce the scientific results that are expected from this experiment. They have been obtained by Monte Carlo calculations. In Fig.12, we stress the importance of measurements in the very forward region for cosmic ray physics. The simulations have been performed using the DPMJET model 3 that includes PYTHIA and PHOJET software. The simulated air showers have an inclination angle of 60 degrees and a primary proton energy $E_0 = 5\times10^{19}\text{eV}$. The bottom curve of Fig. 12 shows the shower development—with pions and Kaons emitted in a region of Feynman variable $X_F > 0.1$ excluded and the middle curve represents the shower curve produced by photons emitted in a region of $X_F > 0.05$ excluded. The top curve of Fig. 12 shows the shower development curve produced by all components of the shower. This graph illustrates how important the contribution of the forward photons with $X_F > 0.05$ is for the total development of showers. The contributions of photons with $X_F < 0.05$ and $X_F > 0.05$ are similar in
magnitude so we must take into account the small number of high energy secondary particles emitted in the very forward region in order to adequately represent shower development.

As the next step, we artificially change the Monte Carlo generator in the region X = 0.01–1.0. Of course the generator has been built to maintain energy conservation. As shown in Fig. 13, the type A production curve deposits its energy deeper in the atmosphere, while the type B cross-section leads to the early development of showers. We do not know if pion production behaves according to curve A or according to curve B or something in between. Without accurate knowledge of the production cross-section of secondary particles in the very forward region, we may mis-identify the primary particle, mistaking protons for iron nuclei and vice versa.

Fig. 13 indicates another very important point for us. If we measure a giant air-shower at an altitude of 900 g/cm$^2$, we can mis-identify the energy of the showers by a factor of 1.75 due to the difference between A and B if say the Monte Carlo uses model A and Nature has chosen B. This possibility may resolve the shower energy debate between AGASA and Utah Hi Res groups that was shown in Fig.1. If we reduce the absolute value of the energy measured by the AGASA group by 20%, then the AGASA and Hi Res data agree rather well, but of course the AGASA group does not agree with this possibility.

### 4.2 Calibration of Monte Carlo codes

In this section we will show how LHCf can identify the applicability of the existing Monte Carlo codes to the very forward production region which is important to high energy cosmic ray physics. Among these codes, the DPMJET I, QGSJET and SIBYLL models are commonly used. Our Monte Carlo calculations show that discrimination between the QGSJET models I and II will be difficult based on the LHCf data for the photon $X_F$ distribution, but we can discriminate between the SIBYLL and the QGSJET models (Fig14) under the reduced $\chi^2 = 2.0$. If we shift the calorimeter 20mm vertically from the beam center, then by comparing the two $X_F$ distributions of photons, the identification between QGSJET model and DPMJET3, SYBILL models will be possible under the reduced $\chi^2 = 6.5$. (Fig. 15). From Fig. 16, if we can measure the neutron energy distribution with 30% resolution discrimination between the neutron generators in the 4 models, QGSJET I, QGSJET II, DPMJET3, SYBILL will be possible. Below we will show that a neutron energy resolution of 30% with LHCf is possible if we select neutron showers that begin in the first few radiation lengths.
Thus our experiment is very important for the justification of various Monte Carlo
codes in the forward region. In this way LHCf will serve as a calibration experiment
for high energy and cosmic ray physics.

---4.3 Monte Carlo Study of Shower Counters---

Here we will discuss the detection efficiency of gamma rays and neutral pions,
based on Monte Carlo simulations. Fig. 17 represents the $E_\gamma$-$P_{TY}$ plot of photons.
The photons that fall in the area under the curve will be detected by LHCf. From this
curve it can be seen that almost all photons with energies higher than 1 TeV can be
detected by LHCf. The photon spectrum is shown in Fig. 18 as a function of $P_{TY}$ and
$E_\gamma$. The arrows indicate the upper $P_{TY}$ bound that can be detected by LHCf. Again
for high energy photons with $E_\gamma > 2$ TeV, photons emitted over a wide range of $P_{TY}$
can be detected. Fig. 19 shows that 78% of the photons with Feynman $X_F > 0.1$ and $P_{TY} < 0.5$ GeV/c can be detected by the detector proposed here. Fig. 20 represents the
acceptance of photons as a function of $X_F$. Almost all photons with $E_\gamma > 1$ TeV, can
be detected.

We will now describe the energy resolution of the proposed shower counter. To
avoid background from low energy photons, we propose to measure the energy
deposited by shower particles beyond 6 r.l. or 8 r.l. Then the expected energy
resolution of the shower counter will be 6.3% and 13.8% for 100 GeV photons and 2.8%
and 5.6% for 1 TeV photons respectively. The energy resolution of the shower
counter is shown in Fig. 21 as a function of photon energy. The calibration of the
absolute energy can be made by using neutral pion peak as shown in Fig. 22.

Next we discuss position resolution. We have evaluated the expected position
resolution for photons of different energies both in Detector #1 and Detector #2 by
using Monte Carlo calculations. The results obtained for Detector #2 (assuming a
readout pitch of 100 $\mu$m) are reported in Figure 23; for example, the expected position
resolution for incident photons with energy 2 TeV is of the order of 160 microns for
Detector #1 and 15 microns for Detector #2. The position of neutrons can be
determined with similar accuracy, for example 170 microns for 1 TeV neutrons.
It is interesting that we can discriminate between neutrons and photons and identify
the energy of neutrons from the shape of the cascade shower as shown in Fig. 24.
Fig. 25 represents the energy resolution of LHCf for neutrons – 30% at 6TeV neutron
energy. The figure has been obtained by a Monte Carlo calculation selecting only
those neutron events (4.1% of the total) which begin to shower in the front of the
detector and have > 20 MIPS in the first r.l.. With this experiment we will have the possibility of measuring the inelasticity K.

Finally we discuss the situation when two photons enter the same shower counter. As shown in Fig 26, this situation cannot be avoided. Approximately 20% of the total photon events will have two photons in the same tower. We propose to remove such data during data analysis by using the SciFi and silicon detectors to identify multiple centers of the shower. Neutron contamination can be discriminated against by the axial shape of the showers and again by using the position measuring systems to identify multiple shower centers when a neutron and a photon are simultaneously present.

5. Preparation up to the submission of the Proposal

1) The SciFi imaging calorimeter with an image intensifier for read–out has been tested using CERN SPS beams. Data demonstrating e/p separation, energy resolution and position resolution have been obtained. The imaging calorimeter has been applied to observe cosmic ray primary electrons above 10GeV in a long-duration balloon flight experiment at the Antarctic.[14] It has also been used to observe atmospheric gamma rays above 5 GeV to calibrate Monte Carlo calculations for the atmospheric neutrino effect observed by the Super–Kamiokande group. [15]

2) We have tested the SciFi–MAPMT read–out system up to 512 channels with ADC in 2002 using the CERN SPS electron and proton beams up to 200 GeV [16]. In 2003, we upgraded the system so that a more realistic calorimeter test could be performed using CERN SPS electron and proton beams up to 150 GeV. A new front–end system (model VA32HDR14) includes one ADC for one Viking chip so that faster data acquisition (> 1 kHz) is possible. More details about the read–out system will be given in Section 7–1.

3) Position resolution better than 0.2mm are expected with both Detectors #1 and #2. This will enable us to construct two–photon invariant mass distributions in which we can see a clear peak of neutral pions (Fig. 22), when each photon hits a different tower calorimeter. Using this peak, we can calibrate our system and thus derive reliable photon and neutral pion energy distributions. In some
events, it may be impossible to resolve two individual photons but such cases are estimated to be less than 20% of total number events as shown in Fig. 26.

4) Our UA7 experience has shown that x, y and u directional deployment of SciFi will enable us to resolve individual photons and determine their energy. The energy and position resolution needed to establish the peak of neutral pions in the photon invariant mass distribution can be obtained with this deployment. (For single photons, the energy resolution at 100 GeV is ~ 2%, therefore getting an energy resolution of 15% for multiple photons is considered to be reasonable).

6. The 2004 CERN test beam results

In the summer of 2004, we performed a test experiment using the CERN North Area H4 beam line. The details of this experiment will be published in a forthcoming NIMA article. The purpose of the experiment was to demonstrate that our calorimeter is suitable for the measurement of high energy photons emitted in the very forward region at the LHC. The 2x2 and 4x4 cm$^2$ calorimeters with 52 r.l. were installed in the beam line and exposed by electron, proton and muon beams. The incident direction of the incoming particles was tagged by a 5 layer of silicon strip tracking chamber with a position accuracy of 3 microns on the junction side and 12 microns on the ohmic side. The detector was made exactly the same size as we are planning to install in the instrumentation slot of the TAN. The photo of the experiment and the detector is shown in Fig. 27.

The main goals of the 2004 SPS experiment were: (1) to investigate the energy resolution of the shower counters, (2) to estimate the corner effect of the small calorimeter, (3) to measure the position resolution of the SciFi detector, and (4) to determine the e/p separation of the calorimeter. There was also an additional goal: (5) to study the position sensitivity of scintillation photons reaching the photomultipliers. The points (2) and (5) address questions that have been raised by the LHCC referee. In this Section we describe the achievement of these goals and the compelling case that LHCf can work in the manner that has been proposed.

Fig. 28 shows the energy resolution of the 2x2 and 4x4 cm$^2$ shower counters for electrons with beam energy 50–250 GeV/c. Monte Carlo calculations can reproduce the experimental results very well. Fig. 29 gives the results of measuring the “edge
effect”, i.e. the case when a shower particle hits near an edge of the calorimeter and some fraction of the shower particles escape from the calorimeter. Fig. 30 shows that the calorimeter can accurately measure the shower energy when the incident electron (photon in the case of LHC) enters 2mm or more inside the edge. The position resolution of the shower counter for electron showers has been obtained by using the SciFi information. The incident position and direction of the electrons was obtained with use of the silicon strip tracking chamber. The silicon strip tracking chamber was located in front of the shower counter as shown in Fig. 31. The tracking chamber can use the position of the incoming particle to predict the shower center with an accuracy of better than 50 microns. Fig. 32 shows the difference of the shower center predicted by the silicon strip detector and measured by the SciFi. The surveying of the detectors was not good enough to exploit the potential resolution of the detectors the results shown in Fig. 32, still give result with resolution of the shower center better than 200 microns.

Fig 33 represents the lateral distributions of shower particles produced by 200 GeV electrons at 10 r.l.. The data were obtained with the 4x4cm² tower calorimeter. The experimental data are compared with the simulation results. In order to obtain the distribution, the center of the shower was determined event by event with use of the SciFi position information. According to Fig. 33, the simulation can reproduce the experimental results. The position resolution of SciFi for determining the shower axis was estimated to be 0.1 mm for photons of a few hundred GeV and is expected to be 0.2 mm for 2 TeV and greater due to saturation of the SciFi. A position resolution of 0.2 mm is sufficient for the goals of the LHCf experiment.

The uniformity of light collection from the plastic scintillators has been also obtained as a function of the transverse position of the shower in the calorimeter. The results are shown in Fig. 34. The variation of light collection efficiency from the center to the corner of a calorimeter is about ±7 %. The data in Fig. 34 can be used to correct for the position dependence of the light intensity collected from the plastic scintillators.

7.1 The read–out system of 64 channel PMT

We have newly developed a read–out system for the SciFi with a 64–multi–anode PMT (Hamamatsu H7546) and an application specific integrated circuit (ASIC). A new Viking chip, VA32HDR14 was especially designed for the ASIC in order to meet the requirements for LHCf. The chip has a wide dynamic range that is required for
measuring the shower profile up to several TeV. The charge output of chip has shown a linear response up to \(-15\) pC.

Since the r.m.s. noise level is 0.8 fC, the dynamic range might be up to 2000 MIPs with the definition that one MIP is 8 fC, which is ten times the r.m.s. noise level. However, the PMT needs to be operated at a gain of around \(10^4\) in order to match the dynamic range of the chip in case the number of photo-electrons from one MIP is \(\sim 6\) for a 1mm square scintillating fiber, Kuraray SCSF38. It is not useful to decrease the PMT high-voltage to reduce the gain since this would decrease the dynamic range of the PMT. Therefore, we have decreased the gain by developing a PMT with the number of dynodes reduced from 12 to 8. This reduces the gain by a factor of 10 and as a result, the PMT output charge is adjusted to realize the full dynamic range of the Viking chip.

Using the ASIC, we have developed a front-end card (FEC) for the analog to digital conversion. The FEC houses a 16 bit ADC for each VA and a Field Programmable Gate Array (FPGA) for the trigger logic. In Fig. 35, the schematic diagram of the FEC and the DAQ system are presented. On one FEC, we have two units. After sample and hold, the 32-channel analog signals are multiplexed in each chip, and converted to digital signals by a single 16-bit ADC. With the trigger condition defined by FPGA, the data are transferred to the VME DAQ system. The PMT high-voltage is also supplied through a FEC. As shown in Fig. 36, the FEC is made of four units that contain two identical sets of cards for 32 channels each on the front and back sides \((32 \times 2 = 64)\). We will use 8 units of FEC in total for the read-out of 512 channels \((64 \times 8 = 512)\), i.e., 8 PMTs. The read-out time of the system used for the SPS beam test in 2004 was nearly 1 ms for one event and was limited by the speed of the ADC and the DAQ to save on power consumption. The current system is much improved in several aspects, for example the ADC with a conversion rate, 1MHz, and a data transfer at high speed, etc. As a result, the required time for DAQ of one event is reduced to less than 100 \(\mu\) s. Another point to be discussed for the read-out system is the so called pile-up problem in the ASIC. Since the VA32HDR14 needs 2 \(\mu\) s to complete the shaping and sample and hold process, the beam intensity must be less than \(5 \times 10^5\) Hz. However in the beginning of the LHC experiment, the luminosity is not so high and collision rate will be around every 1–2 milli-seconds. So with the present system almost all triggered events will be recorded.
7-2. The read-out system of the silicon layers

The silicon strip sensors, used to precisely measure the transverse development of the showers, are readout by means of the PACE3 chips, originally developed for the silicon detector of the CMS preshower calorimeter. They are composed of 2 separate ASICs, mounted together in a fine ball grid array: Delta, that contains the preamplifier and the fast shaping part (25 nsec peaking time), and PACEAM, that houses the 192 cell deep analog memory, clocked at 40 MHz frequency. Each chip has 32 independent channels. The peculiar characteristic of the PACE3 is the large dynamic range (from 0.35 fC up to 1.4 pC), accomplished by means of 2 different gains, user selectable through a I2C standard interface.

The ASICs have been realized with a deep submicron 0.25 \( \mu \text{m} \) technology that can sustain a radiation dose up to 14 MRad without a significant degradation of performance. Each double layer of silicon strips will be read out by means of 48 PACE3 chips, accommodated by 2 hybrid circuits located in the space that is available above the calorimeters.

The maximum dynamic range of the chip is very important for our application, since it is the parameter that could limit the measurement of the impact point of high energy photons on the calorimeter. Hence we did extensive tests to optimize the capability of the PACE3 chips. Figure 37 shows the results that we have obtained by properly optimizing the various stages of the chips. From Fig. 37 we notice that the response of the chip is perfectly linear up to 1.4 pC and the behavior for greater than 1.4 pC will allow measuring input charges up to 2 pC with nonlinearity smaller than 6%.

With this performance and given the readout pitch of our silicon sensors (160 \( \mu \text{m} \)), we start to have saturation effects at the maximum of the shower for incident photon energy greater than 500 GeV. Anyway, the saturation effects are restricted to the narrow core of the shower (with a diameter of the order of few hundreds microns); with a proper fitting of the transverse energy profile we can measure the impact point of the photon with a very good resolution even for photons with energy greater than 2 TeV. For example, the position resolution for 2 TeV photons shown in Figure 23 (15 \( \mu \text{m} \) without taking into account the saturation effects) becomes 23 \( \mu \text{m} \) once saturation is considered.

The signals from the PACE3 chips are digitized by fast 12 bit ADCs, located on the readout boards on the available space above the calorimeter. We plan to use 1 ADC for each PACE3 chip; in this way the readout time for the whole PACE3 chips of silicon system amount approximately to 5 \( \mu \text{sec} \). These boards are then interfaced to
the DAQ boards installed in the VME crate, that houses also the plastic scintillator readout ADCs.

8. Budget, Schedule, Beam Conditions

The proto-type detector was completed in Japan by the end of 2004 using a Grant-in-Aid from the Ministry of Science and Education of Japan. During this period, we have also tested the new read-out system at the CERN SPS. If the LHCC approves our proposal, the additional budget improving the detector will be approved in the fiscal year of 2006. The final detector will be shipped to CERN in early 2006 for exposure to a test beam in either the North or West Areas of CERN in the summer of 2006. The European collaborators will prepare the system for installing the detector in the beam line and a shielding system that may be needed to avoid exposure to radiation when LHCf is not taking data. The LHCf experiment will then be installed in the finalized form and ready for data taking at the beginning of 2007.

LHCf data taking is compatible with the 43 equally spaced bunch pattern envisioned for first LHC physics operation with colliding beams. In order to avoid pileup LHCf needs to operate with bunch spacing 2µsec or greater. In order to avoid contamination of the data with multiple events per bunch crossing LHCf needs to operate with luminosity per bunch less than $2 \times 10^{28} \text{cm}^{-2}\text{s}^{-1}$ and total luminosity less than $10^{30} \text{cm}^{-2}\text{s}^{-1}$. Operation with total luminosity as low as $10^{28} \text{cm}^{-2}\text{s}^{-1}$ would still provide adequate data taking rates. We don’t expect any radiation damage during our experimental period that we expect to last on the order of 100 days. If everything goes well a few hours of recording data will be enough for our purposes; however we require that this be spread over three beam exposures in order to allow time for analysis and evaluation of the data quality.

During the experiment many postgraduate course students from Japan will join and cover the shifts in addition to the present researchers.
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Fig. 1 Energy spectra of cosmic rays at the highest energies. Blue triangles represent AGASA data taken by the Akeno group in Japan with an array of surface detectors, red and black marks represent Hi Res data taken in Utah by the observation of fluorescence in the atmospheres. A clear discrepancy between AGASA and Hi Res can be seen in the region over $10^{20}$eV.
Fig. 2 The position of the shower maximum $X_{\text{max}}$ is shown as a function of the primary cosmic ray energy. The line corresponds to the prediction by the DPMJET model version 2.5 for iron primaries and proton primaries, while the dashed dotted curve represents the predictions by the QGSJET model. The dotted line reflects the prediction by the SIBYLL model version 2.1.
The energy spectra of the highest energy cosmic rays obtained by the AUGER, HiRes and AGASA groups is shown. A 20% reduction of the energy scale of the AGASA data would result in quite good agreement with the HiRes and AUGER data, but of course the AGASA group does not accept this possibility.
The recent energy spectrum of the highest cosmic rays obtained by the Hi-Res collaboration using stereoscopic projection is shown with their former monocular observations. The validity of the Hi-Res stereoscopic data has not yet been officially authorized by the HiRes group.
The vacuum tube contains two counter-rotating beams. The beams transition from one beam in each tube to two beam in the same tube.

The two counter-rotating beams intersect 140 meters away.

There is a mirror image system on the opposite side of the intersection point.

Fig. 5 The beam pipe “Y chamber” 140 m from the interaction point. At this location there is a transition from a common beam pipe in the interaction region to separate beam pipes in the arcs of LHC.
Fig. 6. A blow up illustration of the TAN absorber. LHCf, luminosity instrumentation and copper bar absorbers are to be installed in the 1m long slot between the small diameter beam pipes.
Fig. 7  A precise drawing of the TAN detector region. The small diameter beam pipes are separated by 96 mm and the space between them is occupied by a 1000mm long slot for copper bar absorbers and instrumentation.
Fig 8  The LHCf calorimeter will be located in the first 30cm of the TAN slot between the two beam pipes.

Fig. 9 A schematic view of the LHCf shower counter. It will be composed of three individual tower calorimeters.
Fig 10 Behaviour of a shower produced by a high energy photon inside the tungsten calorimeter. W represents the tungsten plates, Scin corresponds to the 3mm thick plastic scintillators and SciFi stands for the scintillation fiber arrays that are used to determine the shower center.

Fig.11 : The shower calorimeter for Detector #2. The red plates correspond to the silicon strip detectors while green plates correspond to the plastic scintillators. The transverse dimensions of the tower calorimeters are 20x20 mm$^2$, 30x30 mm$^2$, and 40x40 mm$^2$. 
Fig. 12 The transition curve of proton showers calculated by the DPMJET 3 model for $E_0 = 5 \times 10^{19}$ eV. ‘No cut’ means without cutting any kinds of particles. $\gamma : x < 0.05$ means showers created by cutting photons with Feynman variable $x > 0.05$ and $\pi, K : x < 0.1$ represents showers created by cutting pions and kaons with Feynman variable $x > 0.1$. The figure illustrates the importance of high $X_F$ particles for shower development. The LHCf experiment can measure photons with $X_F > 0.05$. 
Fig. 13 Two different production models A and B of secondary particles are presented as a function of the Feynman variable $X$ in the center of mass for primary energy $E_0=1\times10^{17}$ eV. At 900 g/cm$^2$, the number of particles differs by a factor of 1.75. The LHCf experiment can measure photons with $X_F > 0.05$ and thus provide data to discriminate between these models.
The difference in the photon $X_F$ distributions of QGSJET model version I, II, DPMJET model version 3 and SIBYLL. Discrimination between the QGSJET and SIBYLL models with LHCf data will be possible.
Fig. 15 Comparison of the photon $X_\gamma$ distributions predicted by the QGSJET model version II and SIBYLL model. If we compare the photon distribution obtained at different positions of the shower detectors, discrimination between QGSJET, DPMJET version 3 and SIBYLL models will be possible with LHCf data.
Fig. 16  The neutron energy distribution predicted by various Monte Carlo codes. In the calculations a 30% energy resolution for neutron detection has been assumed. This energy resolution is possible for LHCf if neutron showers that begin in the first few r.l. are selected.
Fig. 17  The $E_\gamma$–$P_{T\gamma}$ diagram. High energy photons with small $P_{T\gamma}$ can be recorded by the LHCf shower counter. The red curve is a geometrical cut for our shower calorimeter arising from the configuration of the beam pipe and magnets.
$E_γ = 350 \sim 500 \text{ (GeV)}$

Fig 18  The photon spectrum is presented as a function of $P_{T\gamma}$ and $E_γ$. The smooth curves and vertical arrows indicate the range of $P_{T\gamma}$ accessible by LHCf.
Fig. 19  Production spectra of secondary photons are shown as functions of $E_\gamma$ and $P_{T\gamma}$. The solid curves and vertical arrows indicate the ranges that can be measured by LHCf; 78% of the photons that are emitted with $P_{T\gamma} < 0.5$ GeV/c or $X > 0.1$ can be detected by the LHCf calorimeter.
Fig. 20 The LHCf acceptance of photons. Almost all photons with $E > 1$ TeV can be detected by the proposed calorimeter.
Fig. 21  Energy resolution of the shower calorimeter. At 1 TeV, the energy resolution is 3%.
Fig. 22 The two photon invariant mass distribution for two photons expected for the proposed experiment. The red line represents taking account of experimental errors and the green curve shows when we have taken account of double hits in a single tower calorimeter. According to these Monte Carlo calculations a clear peak at the mass of the neutral pion will be observed by LHCf.
Fig. 23 The expected position resolution of the silicon strip calorimeter (Detector #2).
Fig. 24 The transition curves of the showers expected for photons (black) and neutrons (red). Photons and neutrons can be distinguished by the data in the last layer compared to the shower maximum. The hadron (neutron) induced showers have greater axial extent than the electromagnetic (photon) induced showers.
Fig. 25 This graph represents a 30% energy resolution of LHCf for 6 TeV neutrons. Only neutron events having >20 MIPs in the first r.l. are selected. The fraction of neutrons surviving this cut is 4.1%. The horizontal axis represents the number of shower particles induced by the neutron nuclear–electromagnetic cascade. Only events with shower centers >2mm from the edge have been selected.
Fig. 26 The rate of multiple photon hits in a single tower calorimeter. The fraction of events with more than 5% deposited energy contamination is about 20%. Most of the contamination comes from low energy photons with energy less than 20 GeV.
Fig. 27 (Left) A photo of the shower counter used at the CERN SPS NA test beam experiment. The shower counter was the exact size as the detector proposed here. (Right from the top) Multi anode PMT H7546 mounted on the FEC, SciFi and plastic scintillator.
Fig. 28 The energy resolution of the shower counter measured with 50–250 GeV/c electron beams. Good agreement between the experimental results and the Monte Carlo calculation can be seen.

Fig. 29 The “edge effect.” The total number of shower particles measured in the 2004 beam test is plotted as a function of the distance of the shower center from the calorimeter edge. The effect of particle escape near the edge is clearly seen.
Fig. 30  Escape corrected plot of Fig.29. The energy resolution of the shower counter has been investigated as a function of the shower position. If the shower center is 2mm or more from the edge (as indicated by an arrow), good resolution is obtained.

Fig. 31  Schematic view of the set-up of the test experiment.
The position resolution of the shower center obtained by weighting particle numbers deposited in each fiber. The center of the shower is predicted by the forward silicon strip tracking chamber.

Comparison of Monte Carlo and experimental shower distributions. The shower center can be determined with an accuracy of 0.2 mm which is sufficient for resolving the mass peak of the neutral pions in LHC.
Fig. 34  The light intensity from the plastic scintillators that reaches the PMTs depends on the transverse position of the showers. This arises from geometrical variation of the light path from the shower center to the light guide and optical fiber. The colors indicate measured ADC value which is proportional to the number of photo-electrons on PMT.
Fig. 35  Schematic diagram of the FEC (front end card) and DAQ.
Fig. 36 The read-out system. FPGA: the Field Programmable Gate Array.
Fig. 37  The response curve of the silicon strip amplifier. From the figure we can see that the response of chip is linear up to 1.4 pC and the non-linearity is less than 6% up to 2 pC.