LHCf

Technical Design Report of the LHCf experiment

Measurement of Photons and Neutral Pions in the Very Forward Region of LHC
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Technical Design Report of the LHCf experiment

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1 Overview

1.1 Physics background

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. Extra-galactic 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, 5]. 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 HiRes group has reported a cosmic ray energy spectrum that is consistent with the GZK cut-off [6, 7, 8, 9] as shown as the red points in Fig. 1.

Recently, a few new data points have been collected in the energy range around the GZK cut-off. The Auger collaboration has reported the first result of their experiment at the 29th International Conference on Cosmic Rays in Pune, India, Aug 3-10 2005 as shown in Fig. 2. 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.

Therefore we cannot draw a definite conclusion at present on the existence of cosmic rays above the GZK cutoff. In view of this fact, new air shower projects - Auger [11] and TA [12] – are under way and the EUSO project is under consideration [13]. 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 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.

Figure 1: Energy spectra of cosmic rays at the highest energies. Blue triangles represent the AGASA data taken by an array of surface detectors, red and black marks represent HiRes data taken in Utah by the observation of fluorescence in the atmospheres. A clear discrepancy between AGASA and HiRes can be seen in the region over $10^{20}$ eV.
Figure 2: The energy spectrum of the highest energy of cosmic rays obtained by the AUGER group has been shown together with other data. A 20% reduction of the energy scale of AGASA reproduces quite a good fit to the other data sets.

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 primary cosmic ray composition situation is presented in Fig. 3 [14]. If we use the QGSJET model for the primary interaction model in a Monte Carlo code, the composition of cosmic rays at $2 \times 10^{19}$ eV must be dominated by protons. However if we use the DPMJET2.5 model instead, it is concluded that the composition of cosmic rays is a mixture of several nuclei – protons, helium, carbon and iron – and that 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 the Monte Carlo code calibrated by this fixed data set 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.

Figure 3: 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 DPMJET2.5 model 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 SIBYLL2.1 model.

1.2 Model dependence of air shower development

Here we discuss an example of the impact of model differences in the Monte Carlo simulation of shower development. In Fig. 4, we stress the importance of measurements in the very forward region for cosmic ray physics. The simulations have been performed using the DPMJET3 model that includes PYTHIA and PHOJET software. The simulated air showers have an inclination angle of 60 degrees and a primary proton energy of \( 5 \times 10^{19}\text{eV} \). The top curve of Fig. 4 shows the shower development produced by all components of the shower. The middle curve represents the shower with photons emitted in the region \( X_F > \)
0.05 excluded (this cut also excludes neutral pions with $X_F > 0.10$). The bottom curve in addition excludes all charged pions and neutral and charged kaons with $X_F > 0.10$.

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 know precisely the production cross-section for the small number of high energy secondary particles emitted in the very forward region in order to adequately simulate shower development.

$5 \times 10^{19}$ eV proton initiated showers

*Zenith angle 60 deg.*

![Graph showing proton initiated showers](image)

Figure 4: The transition curve of proton showers calculated by the DPMJET 3 model for primary proton energy $5 \times 10^{19}$eV. The top curve shows the shower curve without cutting any kinds of particles. The middle curve shows the showers created only by photons with Feynman variable $X_F < 0.05$. The bottom curve represents the showers created by pions and kaons with Feynman variable $X_F < 0.1$. 
Next, to see the the impact of model differences in shower development, we change the primary interaction model in the Monte Carlo code in the region $X_F = 0.01-1.0$. The models have been built to fulfill energy conservation. As shown in Fig. 5, the model A production curve deposits its energy deeper in the atmosphere, while model B leads to the early development of showers. We do not know whether pion production can be explained by model A or model 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. 5 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 in shower development between models A and B. This possibility may resolve the shower energy debate between the AGASA and HiRes groups that was shown in Fig. 1. If we reduce (increase) the absolute value of the energy measured by the AGASA (HiRes) group by 20%, then the AGASA and HiRes data agree rather well. This uncertainty must be proven by experimental measurements.
Figure 5: The upper figure shows two different production models A and B of secondary particles presented as a function of the Feynman variable $X_F$ in the center of mass for primary energy of $1 \times 10^{17}$ eV. The lower figure shows shower development curve for both models. At 900 g/cm², the number of particles differs by a factor of 1.75 between the models.

1.3 Impact of the LHCf experiment on cosmic ray physics

Here we discuss the LHCf physics goals and their impact on high energy cosmic ray (HECR) physics.
The important quantities governing HECR air shower development are:

1. the forward production spectra of photons and $\pi^0$'s,
2. the leading particle spectrum and
3. the total inelastic cross-section.

LHCf can provide information on points 1 and 2 but we are not able to access the 3rd point directly. The TOTEM experiment will provide a precise measurement of the total inelastic cross-section. The air shower observation experiments generally rely on Monte Carlo simulations of air showers when they derive the incident cosmic ray energy. Except for the muon component, air shower development is sensitive to the particles generated in the forward region. At energies over $10^{15}$ eV, there is no accelerator calibration of the Monte Carlo codes for the hadronic interaction; so the difference among the codes becomes sizable. For instance, the $\pi^0$ and photon $X_F$-distributions show differences. The leading particle spectra also show sizable differences for $X_F > 0.7$. The leading particle difference is reflected in the leading particle neutron spectrum which we can measure. Cosmic ray interactions in air are not with a proton target, but the nucleus effect in the forward region is expected to be small. Then, we can use LHC pp-interactions to decide which model is best for Monte Carlo simulation of HECR air showers.
Figure 6: The shower development curves obtained from three interaction models, DPMJET2.5, QGSJET, SIBYLL2.1. They predict different atmospheric depth for the shower maximum. The dotted vertical line shows atmospheric depth at the AUGER site. Number of charged particles in the shower at the site depends on the interaction models.

The difference between the models of air shower development appear in the number of electrons and positrons ($N_e$) in the air shower observed at given atmospheric depth. For example, we see a systematic $\sim 20\%$ difference in $N_e$ for $10^{19}$ eV incident proton air at the AUGER site (shown as the dotted vertical line) shower as shown in Fig 6 [14]. Near the shower maximum, the difference is not so large but generally showers are observed over a range of depths. The LHCf can provide information on 1. and 2. and be able to discriminate between the models and reduce the systematic errors due to the difference in Monte Carlo codes. What is important is that none of the codes used in the calculation of Fig. 6 may be close to reality; the LHCf results may produce quite a different spectrum. A systematic difference of $\sim 20\%$ in the flux of electrons and positrons given by the particle production models leads to $50\%$ difference in the flux of primary cosmic rays. This introduces a problems for discussing the following two important issues of cosmic ray phenomena.

- the change of primary cosmic ray species over $10^{17}$ eV. The proton seems to become
dominant species at this energy.

- The existence of the GZK cutoff over $10^{20}$ eV.

The second issue is very important. If the cutoff is absent this will directly lead to new physics for an explanation. The first one is also important not only to know the origin and acceleration mechanism of such high energy particles but also to discuss the component of the super GZK events. The GZK cutoff comes from the fact that high energy protons interact with 2.7K background photons and lose energy and therefore cannot come from distant places. The AGASA group observed super GZK events while the HiRes group gave no super GZK events. The new AUGER experiment is reporting no obvious super GZK events but the energy resolution is not enough at present to draw a definite conclusion on the GZK issue.

If the GZK cutoff exists, there should be also the following pair creation process, $p + 2.7K\gamma \rightarrow p + e^+ + e^-$. This creates a dip in the cosmic ray energy spectrum around $10^{20}eV$. The results of the three groups mentioned above all show some kind of a dip structure in the spectrum. This dip is discussed in detail by Berezinsky [15]. If this dip is regarded as due to the pair creation process, the energy scale of the AGASA group is over-estimated by 10%, the HiRes energy scale is under-estimated by 20%, and the AUGER energy scale is under-estimated by 25% [15].

If this is the case, the AGASA energy estimate is more accurate than the others; it is very interesting to note that the AGASA group shows the super GZK events. If LHCf can guarantee the systematic error in the energy estimation is not more than $\sim 10\%$ or so, the absolute energy calibration by the dip could be reliable and we can discuss the GZK issue on a firm basis.

1.4 Experimental overview

1.4.1 Detectors

The LHCf detectors are small sampling and imaging calorimeters of 29cm length and 9cm$^w \times 60cm^h$ in cross section. We propose to install two detectors located in the TAN ±140m from IP1. With the calorimeters we will be able to identify photons, measure the photon energy spectrum (>$100$ GeV), measure the photon incident position and reconstruct the two-photon invariant mass distribution that shows a clear peak at the neutral pion mass.

At the TAN, 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 7. This “Y-vacuum chamber” is embedded in the massive TAN absorber (Fig. 8) that protects superconducting magnets from IP collision debris.[16] In the crotch of the Y there is a slot (9.6cm$^w \times 60.7cm^h \times 100cm^l$) where ten copper absorbers (each 9.4cm$^w \times 60.5cm^h \times 9.9cm^l$) are installed in absence of detectors. The slot extends from 6.7cm below the beam height to the top of the TAN shielding. At present the LHC luminosity monitor, BRAN [17], 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. LHCf
is not designed to be a radiation hard detector and so would be removed when the LHC luminosity exceeds $10^{30}\text{cm}^{-2}\text{s}^{-1}$. In the absence of LHCf the first three Cu bars would be installed in front of the BRAN.

Figure 7: 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.
The Y-chamber in front of the TAN slot has been carefully machined to have 1 r.l. projected thickness in a 10cm×10cm square centered on the zero degree crossing angle beam line. This assures that a minimum number of particles interact in the beam pipe before reaching LHCf and also that the vacuum chamber does not introduce a bias dependent on the transverse position of the detected showers. The aperture for the detection of neutral particles coming from IP1 is further restricted vertically by the D1 aperture to ±4.4cm at the location of the TAN. This limits the maximum $P_T$ measured and the acceptance for low $X_F$ particles to $X_F < 0.1$. However collisions with 140μrad beam crossing angle in the up-to-down direction shifts the center of the neutral particle showers downward by about 2cm and can extend the measurable $P_T$ region by ~40%. This configuration would substantially enhance the physics results obtained by LHCf. The vertical position of the calorimeter is designed to be remotely changed by ±5 cm in order to uniformly cover the $P_T$ gap to be measured.

However during the early phases of LHCf operation ($< 10^{30}\text{cm}^{-2}\text{s}^{-1}$) and during operation with TOTEM ($\sim 10^{28}\text{cm}^{-2}\text{s}^{-1}$) the detectors would remain fixed and no beam crossing angle would be requested. So from the viewpoint of beam operations LHCf would be a parasitic operation and run with the beam conditions foreseen for LHC commissioning and TOTEM operation.

The two LHCf calorimeters are similar, but not identical for the purpose of redundancy and checking the consistency of measurements. To distinguish between them we will refer them to as ‘Detector #1’ and ‘Detector #2’. The double arm configuration also enable a coincidence measurement of two calorimeters to reduce beam-gas and beam-halo background if necessary.
Detector #1 consists of two towers of sampling calorimeter of 24cm length. They are 2cm×2cm and 4cm×4cm in cross section as shown in Fig 9 stacked vertically and on their diagonals. Both of the Detector #1 calorimeters are composed of 16 layers of plastic scintillator (0.3 cm³) interleaved with 22 tungsten layers of about 2 radiation length (r.l.) to 4 r.l thickness. Total thickness is 47 r.l. This absorber length is sufficient to accurately measure the photon energy up to few TeV.

The plastic scintillators provide fine sampling of shower energy as well as a level 2 online trigger for taking data. In addition there are 4 layers of X-Y hodoscopes made with array of 1mm×1mm scintillation fibers (SciFi) installed at depths of 6, 10, 32 and 38 r.l. and providing transverse position information of the showers. Position resolution for the shower center is expected to be 200 μm. A schematic of Detector #1 showing the PMTs for readout of the plastic scintillators and SciFi and the mounting structure is shown in Fig 10.

Figure 9: A schematic view of the Detector #1. It is composed of two individual tower of sampling calorimeters stacked vertically and diagonally.
Figure 10: A schematic view of the Detector #1 showing PMTs and its mounting structure.

The structure of Detector #2 also consists of two towers of sampling calorimeter with same length as Detector #1. It is similar to Detector #1, but with some differences in the geometrical setup and the position sensitive layers are replaced by silicon strip detectors (Si) as shown in Fig. 11. The tower calorimeters of Detector #2 are 2.5cm×2.5cm and 3.5cm×3.5cm in cross section and stacked on their edges with a horizontal offset to maximize the effective aperture. A schematic of Detector #2 showing the PMTs for readout of the plastic scintillators and Si and the mounting structure is shown in Fig 12.

Shower leakage from the side of the tower calorimeters is corrected by shower position information given by the SciFi or Si detectors. Energy resolution is expected to be $3\% / \sqrt{E(\text{TeV})} + 1.2\%$. The $\pi^0$ mass can be reconstructed in the invariant mass distribution of two $\gamma$'s, one each hitting the two tower calorimeters of Detectors #1 or #2. Typical $\pi^0$ mass resolution is $\sim 5\%$. Good discrimination of hadron (neutron) showers from electro-magnetic (gamma) showers is expected by measuring the longitudinal shower distribution. Energy resolution of hadron showers is expected to be about 30% at 6\,TeV due to longitudinal shower leakage out the back of the calorimeters.

Plastic scintillation counters ("front counters") are installed in the TAN slot in front of Detectors #1 and #2. Their positions are fixed in the TAN and not attached to the
manipulator for moving Detectors #1 and #2 vertically. They tag incoming charged particles and their arrival time.

Figure 11: A schematic view of the Detector #2. The two towers are stacked on their edges. It uses Si strip detectors for position sensitive layers.
1.4.2 Data taking and analysis

We inclusively measure the $X_F$-distribution of $\gamma$'s, $\pi^0$'s by measuring the energy and transverse position of electromagnetic showers. We also measure the neutron $X_F$-distribution by distinguishing between the longitudinal development of hadron and electromagnetic induced showers. The neutron $X_F$-measurement also provides important information for constraining the interaction models used in cosmic ray Monte Carlo codes. For the 2cm×2cm tower centered on the axis of the arriving flux of neutral particles, the typical event rates per inelastic pp collision for $\gamma$'s, $\pi^0$'s and neutrons are about 0.048, 0.0007 and 0.015, respectively. Owing to electronic dead-time for recording data, the maximum data rate for LHCf is 1kHz.

Measured $X_F$-distributions of $\pi^0$'s and $\gamma$'s will be compared with the various models used in cosmic ray Monte Carlo codes. The neutron $X_F$-distribution will give another strong constraint on the models even with 30% energy resolution.

Typical beam parameters we request for the experiment are summarized in Table 1. Although our detector and DAQ system are designed for low luminosity per bunch and 43 bunch operation, it takes only a few hours and a few minutes to obtain $10^4 \pi^0$'s and
$10^5$ single $\gamma$'s, respectively with luminosity $\sim 10^{29}$ cm$^{-2}$ sec$^{-1}$.

The main potential background contaminations will come from beam interactions with residual gas in the beam pipe and interactions of the beam-halo with the beam pipe. The beam-gas background rate corresponding to the start-up beam parameters in Table 1 is negligible ($<1\%$) for the currently accepted estimate of residual gas density inside the beam pipe ($4\times10^{12}$ H$_2$/m$^3$ equivalent). [18]

However if the vacuum conditions are significantly worse than estimated in Ref, [18], the beam-gas interactions can be efficiently removed by selecting events that reconstruct the $\pi^0$ invariant mass. Timing coincidence between Detectors #1 and #2 can also be useful to tag beam-beam collisions and suppress the beam-gas background. According to our estimation, background from beam-halo interactions with the beam-pipe will also be negligible. However if beam-halo interactions with the beam-pipe are significantly greater than anticipated, particularly during early LHC commissioning, then the same strategies for suppressing beam-gas background can be utilized.

<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, 140 $\mu$rad downward</td>
</tr>
<tr>
<td>Bunch separation [$\mu$sec]</td>
<td>2</td>
</tr>
<tr>
<td>Luminosity per bunch [cm$^{-2}$s$^{-1}$]</td>
<td>$&lt;2\times10^{38}$</td>
</tr>
<tr>
<td>Luminosity [cm$^{-2}$s$^{-1}$]</td>
<td>$&lt;0.8\times10^{30}$</td>
</tr>
<tr>
<td>Bunch intensity ($\beta^*=18$m)</td>
<td>$&lt;4\times10^{10}$</td>
</tr>
<tr>
<td>Bunch intensity ($\beta^*=1$m)</td>
<td>$&lt;1\times10^{10}$</td>
</tr>
</tbody>
</table>

Table 1: Summary of beam parameters for LHCf.

1.4.3 Proposed run scenario

LHCf operation is planned in three phases.

Phase-1

Phase-1 is operation during initial beam commissioning and low luminosity running of LHC with 43 bunches per beam, zero crossing angle, $\beta^*=18$m and luminosity less than $10^{30}$ cm$^{-2}$s$^{-1}$. [19]. Phase-1 operation would likely take place during late 2007 and early 2008 depending on completion of LHC construction and start of LHC beam commissioning. Because the radiation hardness of the LHCf detectors is not sufficient for luminosity greater than $10^{30}$ cm$^{-2}$s$^{-1}$, the detectors are removed when the luminosity reaches this level. The contact dose of the LHCf detectors is conservatively expected to be less than $10^{-3}$ to $10^{-2}$ mSv/hr (30day operation at $10^{30}$ cm$^{-2}$s$^{-1}$, one day cool down) and therefore not require special remote handling procedures. The LHCf detectors are then replaced by three Cu bars. Because LHCf and three Cu bars are both nearly two nuclear interaction lengths thick the change in the sensitivity of the BRAN is minimized. However owing to the different transverse cross-section of the Cu bars (which fill the 9.6cm wide TAN slot) and the LHCf calorimeter plates (which for the tower centered on the beam axis is 2cm×
2cm) there will be a reduction in BRAN sensitivity when LHCf is installed instead of Cu bars. The reduction in BRAN sensitivity compared to Cu bars is primarily due to high-energy neutrons from the IP missing the 2cm × 2cm LHCf tower calorimeter and therefore not generating a hadron shower that can be detected by the BRAN. This will reduce the BRAN counting rate by a factor of ~5 to 10 and increase the integration time for a 1% luminosity measurement from 3.6 to ~18 to 36s at $10^{29}\text{cm}^{-2}\text{s}^{-1}$, still reasonably short for LHC Operations purposes. When LHCf is replaced by Cu bars it would be desirable to re-calibrate the BRAN using one of the procedures described in Section 5.5.1.

The level-1 LHCf trigger will be bunch crossings and the level-2 trigger will be a threshold calorimeter signal, similar to the BRAN triggers. LHCf is therefore suitable for use as a luminosity monitor for luminosity $<10^{30}\text{cm}^{-2}\text{s}^{-1}$. By selecting only LHCf events that produce the $\pi^0$ invariant mass, the LHCf luminosity signal will be especially clean and free of background. The LHCf luminosity measurement will be very useful to LHC Operations during early LHC commissioning and operation for corroborating other luminosity measurements. The LHCf acceptance of $10^{-3}$ for $\pi^0$ events and maximum 1kHz data rate determine the integration time for 10% luminosity measurement to be 100s for $L > 10^{28}\text{cm}^{-2}\text{s}^{-1}$.

Phase-1 of LHCf operation will be a parasitic operation with no special requests for beam conditions. It would occur during the early phases of “LHC Commissioning Stage 1” when there are 43 bunches per beam, zero crossing angle, $\beta^* = 18$ m and luminosity $<10^{30}\text{cm}^{-2}\text{s}^{-1}$.

**Phase-2**
Phase-2 is planned when LHC operates at low luminosity $10^{28}\text{cm}^{-2}\text{s}^{-1}$ for the TOTEM experiment, perhaps in 2008. LHCf proposes re-install its detectors to take data during this opportunity and would be removed upon return to luminosity $> 10^{30}\text{cm}^{-2}\text{s}^{-1}$. This would have the purpose of calibrating LHCf against absolute luminosity measured by TOTEM and of providing an opportunity to correct some problem that may have appeared during Phase-1. It should be anticipated that between Phases-1 and Phase-2 the activation of the Cu bars may exceed 0.1 mSv/hr contact dose and require remote handling for their removal and storage. At the end of Phase-2 and before return to high luminosity operation LHCf would be removed and replaced by three Cu bars.

Phase-2 is planned to be a parasitic operation with the beam conditions requested by TOTEM.

**Phase-3**
Phase-3 is a future prospect during heavy ion runs. In this phase, the LHCf detectors must be updated to withstand the radiation dose. A joint experiment with ATLAS is expected during this phase.

It is possible that, after Phase-2 and before removing LHCf, LHCf would request a short run moving the position of one of its detectors and operating with 140μrad downward crossing angle in one beam for the purposes of extending the range of accessible transverse momentum by ~40% and also filling in the (transverse momentum between the two towers of LHCf. The sensitivity of only one of the BRAN would be affected so the other would provide continuous luminosity measurement during this time.
2 LHCf detectors

2.1 Calorimeter overview

A pair of small sampling calorimeters (Detector #1 and Detector #2) will be installed inside each TAN absorber ±140m from the ATLAS collision point IP1. The two detectors are similar, but use different techniques and geometry for the purposes of redundancy and consistency checks of the measurements. Each detector has two sampling and imaging calorimeters arranged in a tower. The calorimeters consist of tungsten plate converters interleaved with plastic scintillators. Typical fluxes of neutral particles above 100 GeV incident on LHCf are about $2 \times 10^{-2}$ cm$^{-2}$ per pp interaction at the center of the flux of incoming neutral particles and about $8 \times 10^{-3}$ cm$^{-2}$ 3 cm above the center. The transverse dimensions of each tower are optimized to reduce multiple particle hits in a single calorimeter and to give similar counting rates in the two calorimeters.

The range of shower energy measured by LHCf is from ~100 GeV up to several TeV. Fig 13 shows typical behavior of a shower produced by a high energy photon incident on LHCf. The typical number of particles at the shower maximum is roughly expressed as $E(\text{TeV}) \times 10^4$ MIPs. The number of particles traversing the plastic scintillators ranges from 100 MIPs to several $10^4$ MIPs as shown in Fig. 14 for the case of a few TeV $\gamma$ shower. Thus the plastic scintillator layers must cope with this wide dynamic range (100 ~ $10^5$ MIPs) with reasonable linearity.

![Diagram of LHCf calorimeter](image)

Figure 13: Behavior of a shower produced by a high energy photon inside the tungsten calorimeter. W represents the tungsten plate, Scin corresponds to the 3mm thick plastic scintillator and SciFi stands for the scintillation fiber arrays that are used to determine the shower center.
Transition curve

47 TeV neutron (red) vs 2 TeV gamma (black)

300 GeV neutron vs 100 GeV gamma

Figure 14: The transition curve of the showers expected for photons (black) and neutrons (red). If we take account of the information in the last layer, we can separate photons from neutrons.

Since the Molier radius of tungsten (= 0.93 cm) is comparable with the transverse calorimeter dimensions, shower leakage out the sides of a tower will affect the measurement of shower energy. We introduce position sensitive layers in order to correct for this effect by measuring the position of the shower axis. The lateral shower shape is also capable of identifying multiple particle hits in a calorimeter. The two calorimeters of a tower are stacked with a little gap of a few mm between them to reduce shower leakage out the side.
of one into the other.

The tower arrangements of the two calorimeters for Detector #1 and Detector #2 are shown in Fig. 15 and Fig. 16, respectively. These configurations have been chosen to satisfy some basic requirements, related to the physics goals of the experiment, to the simplification of the structure of the detector and to the improvement of its performance.

First of all it should be underlined that the free space region in the TAN where LHCf can collect interesting data is strongly limited. The main reasons for this limitation are essentially two. The first is the structure itself of the slot where LHCf will be lodged. In fact, while in the vertical direction it is only downward limited because of a metal plate positioned 6.7 cm below the beam line center, in the horizontal direction, transverse to the beam line, the slot has a width of 96 mm. This is due to the fact that the distance between the two beam pipes near the recombination chamber (i.e. inside the TAN) is only 96 mm. The second factor that sets a limit for the 'good' region of LHCf is the structure of the beam pipe between IP1 and the TAN location. Considering the neutral particle trajectories between the interaction point and the TAN it is found that the maximum aperture for which these trajectories are fully contained inside the vacuum pipe is defined by the structure of the pipe itself in the dipole region, around ±84.5 m far from the IP. In this region the vacuum pipe is elliptical with horizontal and vertical axes 128 mm and 53 mm, respectively. The projection of the D1 aperture to LHCf ±140 m from the IP is an ellipse with horizontal and vertical axes 211.8 mm and 87.7 mm, respectively. Neutral particles entering the TAN outside this elliptical region have thus passed through the vacuum pipe walls or have been produced in some interaction not at the IP. Details relating to the aperture description just given can be found in Figure 16, where a transverse projection of the proposed detector structure and the limits of the accessible 'good' region are drawn. The calorimeter positions have been chosen to cover the largest rapidity range allowed by the discussed constraints.

Detector #1 is optimized for the case that the LHCf can vertically move or 140 μrad beam crossing angle is realized. On the other hand, Detector #2 is optimized to enlarge the scientific performance in the limited aperture. The smallest tower (2.5 × 2.5 cm²) is arranged along the beam line. The largest one (3.5 × 3.5 cm²) is used to cover the part of the 'good' region that extends out to the limit of the aperture defined by the TAN slot and the D1 beam pipe.
Figure 15: Transverse projection of Detector #1. The elliptical structure of the beam pipe between IP1 and the TAN location (that is the main limitation to the acceptance of LHCf) and the internal walls of the TAN are also sketched.
Figure 16: Transverse projection of Detector #2. The elliptical structure of the beam pipe between IP1 and the TAN location (that is the main limitation to the acceptance of LHCf) and the internal walls of the TAN are also sketched.

The sizes of the two calorimetric towers are slightly different than Detector #1 because they have been optimized considering the dimensions of the Si sensor that have been described in details in Section 2.3.1. The arrangement of the calorimeters shown in Fig. 16 has also been optimized for separation of the Si sensor signals when there simultaneous showers in the two calorimeters. The sensors are arranged in such a way that the microstrips are aligned in the vertical direction or in the horizontal direction. It is thus clear from Fig. 16 that the Si sensor geometry does not allow a single Si strip to run over both calorimeters.

2.2 Detector#1

Detector #1 is composed of 2 individual calorimeters arranged in a tower structure as shown in Figs 9 and 10. The calorimeters have 24cm length and are stacked vertically with a 5mm gap between them. The lower detector and upper detector have cross section of 2cm×2cm and 4cm×4cm, respectively. Their acceptance covers the diagonal areas shown in Fig 15 together with the masking by the beam pipe in the D1 magnet. Figure 17 shows the diagonal calorimeters of Detector #1 with their light guides and PMTs. The calorimeters are composed of 22 tungsten plates, each plate having a thickness of 2 radiation length (r.l.) for the first 11 layers and 4 r.l. for rest of layers as shown in
Fig 19. The total thickness of each calorimeter is about 48 r.l, including 1 r.l, for the projected thickness of the Cu Y-chamber. This absorber length is sufficient to accurately measure the photon energy up to a few TeV. Tungsten plates are interleaved with thin plastic scintillators (0.3cm³) of the same dimension as the tungsten plates. The scintillation photons are read out by a small PMT for each scintillator. The scintillators measure the total deposited energy and provide a level-2 online trigger signal for the DAQ. The level-1 trigger is synchronized to the bunch crossings. Total number of scintillator layers is 16 per calorimeter so that 32 PMTs are used in total. In addition there are 4 layers of X-Y hodoscopes made with arrays of 1 mm×1 mm scintillation fibers (SciFi) installed at depths of 6, 10, 32 and 38 r.l, and providing transverse position information of showers. Position resolution for shower center is expected to be 200 μm. The SciFi are readout by multi-anode PMTs (MAPMTs). Two calorimeters are embedded in a detector housing of 9cm⁸×60cm¹×29cm¹ together with 32 PMTs, 8 MAPMTs and the front-end electronics box shown in Fig 19. The housing is mounted to the manipulator which can remotely move the detector vertically by about ±5cm. All the signal and other cables run through the top panel of the housing and are connected to a patch panel placed near a cable tray at the location of the TAN in the LHC tunnel.
Figure 17: Front cut-away view of Detector # 1 showing structure of the calorimeters, flexible light guide fibers, PMTs, MAPMT front-end circuit box and inner cabling. The right figure is an enlarged view of the left one.
Figure 18: Front cut-away view of Detector # 2 showing structure of the calorimeters, flexible light guide fibers, PMTs, Si layers, their front-end circuit boards and inner cabling. The right figure is an enlarged view of the left one.
Figure 19: Side cut-away view of Detector #1 showing the structure of tungsten and scintillator layers, PMTs and their mounting structure, MAPMTs and their front-end circuit box.
2 Towers, Arm#2

30-jan-2006

note: Because we do not have MAPMT FEC, we can use full of 90mm width for PMTs.

Figure 20: Side cut-away view of Detector # 2 showing the structure of tungsten and scintillator layers, PMTs and their mounting structure, Si layers, and their front-end circuit boards.

2.2.1 Plastic scintillator layers

Thin plastic scintillator plates (0.3 cm$^2$) are installed at every 2 to 4 r.l. for triggering and for measuring the total deposited shower energy. We use a slow plastic scintillator
EJ-260) made by Eljen Technology Co. The typical decay time of 9.2 ns is suitable for preventing saturation of the PMTs by the large incident photon flux at the shower maximum. Photons from each scintillator layer are collected by an acrylic fish-tail like light-guide and then readout by small PMTs (HAMAMATSU R7400U through a bundle of 1mm$^3$ clear optical fibers (KURARAY CLEAR-PS) as shown in Fig 17. The typical number of photo-electrons(p.e.’s) is about 10 p.e./layer for the energy deposited by 1 MIP.

The HAMAMATSU R7400U has 8 stages of metal channel type dynodes. They have the important feature of good linearity even with relatively low HV operation. We need to operate at low HV to cover the wide dynamic range of the energy deposited by $10^2$ MIPS to $10^5$ MIPs. We additionally optimize the HV value for each dynode stage to reduce the non-linearity to less than $\sim 10\%$ with low gain (HV) operation, even for the shower maxima of several TeV photons, which lead to the energy deposited by several times $10^4$ MIPs. Figure 21 shows PMT linearity for various HV values checked with $N_2$ laser system (see Section 3.7.1). Nominally the PMTs will be operated with $\times 1000$ gain with HV = -550V. The maximum gain is $10^5$ with HV = -1000V.

The output signals of the PMTs are fed to pre-amplifiers at the patch panel and then amplified by factor of $\sim 10$ and sent to the counting room in USA15.

![Graph](image)

Figure 21: The PMT response as a function of incident number of photons for various HV setting. The data was obtained by $N_2$ laser calibration.

### 2.2.2 SciFi layers

To identify the position of a shower and to resolve the positions of multiple showers in a single calorimeter, X and Y hodoscopes are prepared, each of which consists of an array of 1 mm×1 mm square scintillating fibers (KURARAY SCSF-38). Signals from the SciFi are read out by using multi-anode (=64) photomultipliers (MAPMT), HAMAMATSU H7456. The 4 SciFi layers are installed at depths of 6, 10, 32, and 38 r.l.. The two layers
at 8 and 10 r.l. are used for the identification of the center of electromagnetic showers and the layers located at 32 and 38 r.l. are used for the identification of the shower center of neutron induced nuclear cascade showers. The total number of fibers are 160 and 320 for the small tower and the large tower, respectively. In total 8 MAPMTs are used for reading out the SciFi.

2.3 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 2 calorimetric towers, 2.5 cm×2.5 cm, 3.5 cm×3.5 cm, positioned as shown in Figure 11. Two calorimeters are stacked on their edges and offset from one another. This configuration enhance the maximum $P_T$ region to be measured by Detector # 2 and provides redundant information with different geometry to compare to Detector # 1. Each calorimeter is 24 cm long. It has the same longitudinal structure already described for Detector # 1 and similar read out structure for the plastic scintillator layers for calorimetry. However the SciFi layers for the determination of impact point are replaced by layers of Silicon micro-strip detectors. In particular we will install 4 double layers of Si 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 6, 10 and 38 r.l. as shown in Figure 11.

2.3.1 Si tracker

Each double layer of silicon sensors is in turn composed by 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 about 6.4×6.4cm² wide, and are realized by means of square sensors rotated one with respect to the other by 90°. The sensor that we propose to use has been selected out of existing sensors developed for the LHC experiments and has been produced by Hamamatsu Photonics to be used for the barrel part of the Semiconductor Tracker of the ATLAS experiment (ATLAS/SCT, model S8536-02B). This sensor is single sided and has a total surface of 6.3560 ×6.3960 cm² (with a overall dicing tolerance of around ± 25 μm) and a thickness of (285 ± 15) μm. The microstrips are aligned parallel to the longest side. The ohmic side of this sensor is passivated with a simple metalization that allows the inverse polarization of the sensor. The maximum declared full depletion voltage is 150 V. On the junction side 770 microstrips are implanted with an implantation pitch of 80 μm. The outer two are spare microstrips to be used as field-shaping and charge-control strips. The sensitive region, where the microstrips are physically implanted and the charge produced by ionizing particles can be collected, is 6.1680 ×6.2000 cm² wide. The bias resistors are (1.25 ± 0.75) MΩ polysilicon resistors which are separated by the surrounding bias ring by a 6 μm punch-through protection gap. The passivation of the junction side is realized by mean of a SiO₂ layer, over which the metal readout strips are deposited. Two bonding pads 56 × 200 μm² are shaped at each end of the metal strips. More detailed information
can be found in the ATLAS SCT web site [20].

Dedicated kapton fan--outs will be used on both X and Y layers, to allow the readout strips to be connected with wire bondings to the hybrid circuits; these circuits, and the front-end 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 and the performances will be good enough for the physics goal of LHCf, as it will be pointed out in Section 4.1.1. In this way the total number of readout strips amounts to 3072. The front-end and readout electronics of the Si system will be described in detail in section 3.4.

2.4 Front counters

A counter utilizing plastic scintillator is being considered for installation in front of each LHCf detector. They are mounted in the most forward position of the TAN slot at and not attached to the tower calorimeters. Their position is fixed, while the tower calorimeters may move vertically. They can measure the flux of any charged particles entering the calorimeters. They could provide a veto for showers starting in the beam pipe and timing information of beam collisions at the IP. They are thin and the total length of the LHCf calorimeters and Front Counters will not occupy more than the 30cm length of three Cu bars in the TAN.

2.5 Integration with TAN and BRAN

The TAN are massive ~30 Tonne absorbers designed to protect the outer beam separation dipoles D2 from neutral particle debris from pp collisions at the IP. The TAN are located ±140m on each side of IPs 1 and 5. Each TAN contains a 9.6cm wide by 100cm long by 60.7cm deep slot immediately behind the crotch of the Y beam vacuum chamber and centered on zero degree horizontal crossing angle. The nominal beam height (zero degree crossing angle) is 6.7cm from the bottom of the slot. In the absence of instrumentation this slot is occupied by ten 9.4cm wide by 9.9cm long Cu bars inserted vertically in the TAN. The height of the Cu bars is 60.5cm and their weight is 50.6kg. At present the LHC luminosity monitor BRAN [17] is designed to occupy the position of the fourth copper bar and the LHCf detector is designed to occupy the position of the first three copper bars. At the top of TAN surface, there are three survey markers. The support structure and the height of the LHCf detector are designed to keep clear of the lines of sight to the survey markers as shown in Fig 22. On the aisle side of the TAN, small front-end electronics boxes will be mounted for the readout of Si layers..
Figure 22: Front cut-away view of TAN and LHCf integration showing the area occupied. Manipulators and front-end circuit box for Si layers will be mounted on TAN surface.
2.5.1 Manipulator

The LHCf detector is supported by a manipulator that can remotely move the vertical position of LHCf by ±5cm with respect to the beam line for zero crossing angle. The idea of the manipulator is shown in Fig 23. The detector is supported by the movable stage controlled by a stepping motor with position readout. Accuracy of location is designed to be ∼100μm. The manipulator will be mounted to the top surface of the TAN with screw bolts. The actual design of the manipulator is under discussion. We are carefully selecting from the existing products of linear stage to keep a clearance for the survey work.

2.5.2 Installation

There is enough open space above the LHCf detector that the detector can be installed in the TAN from above. As we discuss in Section 5, the LHCf detector will be installed in the place of the first three Cu bar absorbers in the TAN sometime between end of 2006 and early 2007 before closing access to the tunnel. This installation work will take 4 weeks in total including in-situ PMT gain calibration of each detector. During the period up to LHC beam commissioning, shake-down of the detector and electronics, noise survey, calibrations and integration of the DAQ, etc. will be completed.
The total weight of the LHCf detector and manipulator are ~20 kg and ~9 kg, respectively. So any simple standard cranes should be adequate for safe installation. When the LHC luminosity approaches the level of \( \sim 10^{30} \text{ cm}^{-2}\text{s}^{-1} \), the LHCf detectors will be removed and three Cu bars installed in its place. As we discussed in Section 2.5, the contact dose at the LHCf detector is conservatively estimated to be \( 10^{-3} \) to \( 10^{-2} \) mSv/hr (30 day operation at \( 10^{30} \text{ cm}^{-2}\text{s}^{-1} \), one day cool down) and therefore not require special remote handling procedures when it is removed after Phase-1 operation.

Between Phase-1 and Phase-2 operation the contact dose of the Cu bars may exceed 0.1 mSv/hr and require remote handling for their removal. Under all LHC operating conditions the contact dose of the outer surface of the TAN shielding will remain below 0.1 mSv/h and allow access to the tunnel.
3 Data handling and electronics

3.1 Cabling

The electronics and DAQ computers will be placed in two electronics racks (Y.26-05.A1 and Y.27-05.A1) in USA15, the ATLAS counting room area. Patch panels are to be prepared at the tunnel wall near each TAN and in USA15. Figure 24 and Fig. 25 show schematic diagrams of the cable routes from the TAN area to USA15. All the cables and connectors in the tunnel will be standard halogen-free parts commonly available in CERN.

There are 32 LEMO type cables for Detector #1 and Detector #2 from the R7400U PMTs for the plastic scintillators to the pre-amplifier at the patch panels near the TANs. The PMT signals are amplified by about a factor of ~10 and transferred to USA15 by 200m of BNC type cables (C-50-3-1, 4.23ns/m). These cables run through a short-cut path in the “Survey Gallery” to USA15 to minimize signal delay and attenuation. The attenuation of pulse charge and height will be about 50 % and 20 %, respectively. Signal delay is about 846ns.

SciFi data are processed by on-board FECs (Front End Circuits) inside Detector #1. There are two 75Ω BNC type cables and three 50Ω BNC-type cables for SciFi data transfer and control. DC power for the FECs is supplied by 6 low voltage power supplies ( current<3A ). Thirty three SHV-type HV cables for the R7400U and H7456 PMTs are fed to the patch panel then transferred to USA15 with one multi-conductor cable. For Detector #2, 2 bundles of 96 optical fibers, which are commonly used in CMS, will be used for the Si strip FEC readout. Five high-current low voltage cables and ~10 low-current low voltage cables are used for the Si strip FECs. Including the manipulator control cables, slow monitors and other utility cables, about ~60 cables in total from each detector will run through the tunnel. In addition, CERN standard digital optical fibers will supply the level-1 trigger to the TAN site. Also analog optical fibers which distribute laser light to the plastic scintillation layers are being considered for in-situ run-time calibration.
Figure 24: Schematic diagram of cabling between the TAN and USA15 for Detector #1.
3.2 Read-out system for plastic scintillators

A Schematic diagram of the electronics at USA15 is shown in Fig 26. As mentioned above, the signals from R7400U PMTs are amplified typically by a factor of ~10 at the pre-amplifier and transferred to USA15. Then the signal is split into two and one is fed to the 16-ch VME discriminator (CAEN V814) to form triggers and the other is fed to the 16-ch VME-ADC (CAEN V965) for recording the shower event.

The PMT discriminator threshold is set to several mV which corresponds to the shower maximum of 100GeV photons (~10^4 MIP’s). The CAEN V965 is a 15-bit high-sensitivity ADC with two dynamic ranges. The low-range and high-range have 0.025pC/cnt (~100pC
max) and 0.2pC/cnt (∼800pC max) respectively. Both of the two ranges are always available so that sufficient resolution and dynamic range are always obtained. The conversion time of the ADC is 7µ sec. However if a “first clear” signal is fed to the ADC anytime after the ADC gate the integrated charge can be cleared. The dead time of the “first clear” is 600ns. Read-out time of data buffer for all channels takes about 1ms which limits the maximum DAQ rate as 1kHz.

With a nominal ∗1000 gain for the R7400U PMTs, the deposited energy equivalent to 10³ MIP’s gives a ∼1.6pC pulse with ∼8mV pulse height into 50 Ohms at the PMT output. Taking into account the pre-amplifier gain (∼10 ) and the attenuation by 200m of cable (50% reduction for charge, 20% reduction for pulse height), and divider ratio (1 to 2), the pulse height at the discriminator and the charge at the ADC are 8mV and 4pC respectively. This pulse height is enough for the discriminator and for the ∼mV noise level we assume. For the ADC, 4pC corresponds to 160 counts on the low-range. For a 7TeV primary the charge at the shower maximum becomes 400pC corresponding to 2000 counts on the high-range of the ADC and is still within the ADC range.

Figure 26: Schematic diagram of electronics for DAQ.

3.3 Read-out system for SciFi

The signals from the multi-anode PMTs for the SciFi are processed by a VA and TA chip on the front-end board as shown in Fig 27. We have recently 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 the wide dynamic range that is required for measuring the shower profile up to several TeV. The charge output of the chip has shown a linear response up to -15 pC.

Since the r.m.s. noise level is 0.8 fC, a dynamic range of 2000 is attainable 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 $\sim6$ for a 1mm square scintillating fiber, KURARAY SCSF-38. 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. 28, 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. 27, the FEC is made of four units that contain two identical sets of cards for 32 channels each on the front and back sides (32×2=64). We will use 8 units of FEC in total for the read-out of 512 channels (64×8=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 now has a conversion rate of 1 MHz, and a high speed data transfer rate, etc. As a result, the required DAQ time for one event is reduced to less than 100 µs. Another point to be discussed for the read-out system is the so called pile-up problem in the ASIC. Since the VA32HDR14 needs 2μs to complete the shaping and sample and hold process, the pp beam interaction rate must be less than $5\times10^5$ Hz. However in the beginning of LHC commissioning and physics operation when the luminosity is $\sim10^{29}$cm$^{-2}$s$^{-1}$ the level-2 trigger rate for single gamma showers will be around 500 Hz and the present system will record almost all events.
Figure 27: Schematic diagram of the FEC (front end card) and DAQ for the SciFi.

Figure 28: The FPGA (the Field Programmable Gate Array) read-out system for the SciFi.
3.4 Readout system for the Si layers

The Si detector read-out has capitalized on previous LHC experience. We have opted for electronics capable of working with a 25 ns beam-crossing rate and in a high radiation environment. Thus we have used fast shaping integrators for our silicon microstrip detectors and a clock and trigger distribution architecture based on the TTC system from CERN. Our digitizers also use chips specifically developed for LHC.

The Front End Hybrid (FEH) which is glued and bonded to the detector is based on the PACE3 chips developed for the CMS silicon pre-shower [21]. They are composed of 2 separate ASICs, each with 32 independent channels, packaged together in a ball grid array. One is the Delta chip that contains the charge integrator and the fast shaper (25 ns peaking time), the other is the PACEAM that houses the 192 cell deep analog memory with the output multiplexer. The peculiar characteristic of the PACE3 is the extremely large dynamic range (from 0.35 fC up to 1.4 pC), which is accomplished by 2 different gains, user selectable through a standard I2C interface. The ASICs have been realized with a deep submicron (0.25 μm) technology that can sustain a radiation dose up to 14 MRad without a significant degradation of performance.

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 29 and Figure 30 show the results that we have obtained by properly optimizing the various stages of the chips. From these figures we notice that the response of the chip is perfectly linear up to 1.4 pC with a nonlinearity smaller than 6% for input charges up to 2 pC.
Figure 29: Plot of the PACE3 signal shape for different injected charges; the plots have been obtained by properly optimizing the various stages of the chip.

Figure 30: Charge linearity plot obtained for the PACE3 chips.

Given the number of strips to be read-out for each sensor (384), each FEH will use
12 PACE3 chips. The FEH itself is divided into two sub-assemblies each independent of the other and capable of reading out 192 strips (see Figure 31). Each half of the FEH contains a Multilayer PCB that houses chips and passive components, and a gold on kapton pitch adapter that connects the PACE3 inputs to the silicon sensor. The kapton pitch adapter is glued to the PCB itself. Wire bondings are used to connect the silicon strips to the pitch adapter. On each half-FEH, we have placed a DCU (Detector Control Unit) chip, together with the PACE3 chips, which will monitor temperature and voltage levels, and various LVDS and CMOS buffers. All these chips have been developed for the CMS tracker and the CMS electromagnetic calorimeter.

The control and readout of the FEH chips are done via a Front End Driver board (FED) which houses both control chips and analogue signal digitizers. We will now describe the control part of the board, leaving the digitizing part to the end. The control architecture followed closely resembles that adopted by the CMS silicon tracker (Figure 32). The TTC (Trigger, timing and control) signals from the LHC machine and from the LHCf calorimeter are sent to the TTCci (CMS TTC interface) module and to the optical FEC (Front End Controller) module [22].

The two modules (the TTCci module is not shown in Fig 32) sit inside the ATLAS counting room and transmit clock, trigger and data signals via optical fibers to the transceivers placed near the detector inside the LHC tunnel. The whole control chain has the structure of a token ring. The token is sent from the FEC to the CCUMs (Communication Control Units Modules) via DOHs (Digital Opto-Hybrids) and, after going around, gets sent back to the FEC itself. The optical FEC used has two independent transceivers which are coupled to a redundant ring architecture. Thus if any component on the ring fails one does not lose all four silicon modules but only a single one. Each CCUM distributes I2C commands, the 40 MHz clock and the trigger for a single Si detector (one FEH) [23]. Through the FEC then, we not only distribute ”fast” signals, i.e. clock and trigger, but also ”slow” controls like register settings present on the PACE3 chips and assorted PLLs and DCUs, temperatures and voltages. To this purpose each CCUM has 16 I2C buses and other programmable I/O ports. Nonetheless a few temperature probes will be hard wired through an independent channel (see Section 3.5) so that ambient conditions may be known before switching on the electronics.

On the FED main board there are also two piggy back carriers on which the ADCs are placed. The analogue signal from the PACE3 chips are digitized using the AD41240 developed specifically for CMS ECAL. The digitized data are then processed by the ALTERA gate array and sent for transmission to the Gigabit Optical Link (GOL). The GOL interfaces, through optical fibers, to the DAQ PC in the ATLAS counting room. In Figure 33 a schematic diagram shows the main components of the silicon FED board.

One ADC chip is capable of handling 4 PACE3 chips outputs with a 12 bit resolution. The digitized information is available through two 12 bit multiplexers clocked at 40MHz. This scheme allows reading out a silicon detector in roughly 7 μs. The data is formatted and stored temporarily in the FPGA and then sent through the GOL. Without zero suppression the maximum time to transmit data from a whole module (24 PACE3 chips) is of the order of 50 μs. The FPGA used is a flash programmable device with embedded storage and processing power which can eventually be used for data treatment before
sending. The silicon DAQ system thus would consist of four FED boards plus one DOHM board which houses the DOH transceivers. These boards are to be installed in a mini-crate that sits on the side of the TAN close to the detector.

Before describing the powering of the FEH and related boards, we would like to mention that the use of a FE chip like the PACE3, which has a peaking time of 25 ns, poses a stringent request on the timing accuracy of the calorimeter trigger. Jitter greater than 25 ns could jeopardize the performance of the silicon tracker.

3.5 Power supply system for the Si detectors

The Si detectors, together with the FEH, require one HV bias and one 2.5 V source. The DAQ boards require both a 2.5 V and a 3.3 V source. Current needs are typically 2.5 Amps for each FEH (24 PACE3 chips) and 2-3 Amps (@2.5V) and 1-2 Amps (@3.3V) for each FED board. These power requirements can be satisfied by the use of local boards with rad-hard regulators (Telecommunications RHFL4913) which distribute low voltages to the FEHs and FEDs. Besides low voltages these boards will filter the HV needed for detector biasing. The power distribution boards themselves are powered by a CAEN Easy 4000 system (with SY2527 Main Frame) through 200 meter long cables (see Figure 34). The system has been developed for the CMS tracker and uses remote sensing to compensate voltage drops on the cables. Its safety features that concern the powering of the Si detectors, include overcurrent and over-voltage alarms, programmable trip conditions and hardware interlocking. Table 2 shows the main power requirements for each Si module.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>IFEH (A)</th>
<th>IFED (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 V</td>
<td>2.5 A</td>
<td>2-3 A</td>
</tr>
<tr>
<td>3.3 V</td>
<td>0 A</td>
<td>1-2 A</td>
</tr>
</tbody>
</table>

Table 2: Current requirements for each Si module. Four such modules are needed for LHCf.

Together with the cables used for powering, we plan to deploy twisted pairs to read out hard wired temperature sensors (PT1000) and humidity sensors. These can either be connected to a local slow control system, or to a DCS/DSS provided by LHC.
Figure 31: Schematic drawing of a Front End Hybrid. The two halves are mirror copies of each other. The pitch adapter connects the silicon strips to the PACE3 inputs. Signals travel through the rear-end connector.

Figure 32: Control ring architecture followed for the LHCf silicon detectors. The Front End Control board sits in a PC in the counting room. Signals travel through optical fibers down to the cavern where the rest of the electronics sit. The two signal pathways are identical and provide the needed redundancy (see text).
Figure 33: Schematic diagram of the FED mainboard. Trigger decoding, I2C commands, and data digitizing and formatting are done on this board which sits in close proximity to the detector. All links to the control room are through optical fibers.
3.6 Trigger logics and data acquisition

A trigger diagram is shown in Fig 26. Two levels of triggers will be used. The level-1 trigger is an occupied bunch crossing signal. It opens an ADC gate for the plastic scintillators. The level-1 trigger is also fed to the Si layer front end board.

A hit signal for each scintillator layer is formed by a VME-discriminator. The threshold will be set to several mV which corresponds to a scintillator signal for the shower maximum of a 100 GeV photon. The level-2 trigger is then formed by a coincidence of scintillator hit signals from any adjoining 3 layers of scintillator. These coincidences are done by a custom VME trigger board utilizing FPGA chips. The level-2 trigger is then fed to the SciFi FEC to invoke ADC for the sample and held pulse heights of the MAPMT which are designed to be held for 1.8 µsec. The decision time of the level-2 trigger should be less than 100ns after the PMT signals reach USA15. If the level-2 trigger is not fired within the time-out after the level-1 trigger (~100 ns), a fast clear signal is fed to clear VME-ADC. It takes about 800ns to complete a fast clear. The DAQ computers start to record data whenever the level-2 trigger from either of the two calorimeters fires.

The entire trigger sequence will be finished within 2 µsec. The total decision time after a bunch crossing signal is received at USA15 is less than 1.4 µs (140m×3.3 ns/m + 846 ns +100 ns). This is fast enough to feed the “LHCf self-trigger” to the ATLAS trigger sequence.

The time difference between the level-1 trigger (i.e. bunch crossing) and the level-2 trigger from each arm of LHCf is also recorded. We use two independent VME on-board Linux computers for taking the data from Detector #1 and Detector #2. An event builder running in a 3rd computer will merge the data from both Detectors. The data taking rate is limited to about 1kHz. When the LHC luminosity exceeds 10^{29} cm^{-2}s^{-1}, LHCf can still take data as long as the bunch-to-bunch spacing is still 2 µs.

Coincidence of the level-2 triggers from two calorimeters in same detector also provides a possible π^0-trigger. The typical trigger rates are ~600 Hz for γ’s and ~10Hz for π^0’s with 10^{29} cm^{-2}s^{-1} luminosity. For the higher luminosity case, a level-2 coincidence trigger between two calorimeters in the same arm can be used to enhance statistics of π^0’s in the
sample with limited DAQ performance.

3.7 Calibration

3.7.1 Laser calibration

It is very critical to check the linearity of the PMTs for scintillator layers in the range of $10^2$ MIPs to $10^5$ MIPs. Since the linearity response of a PMT depends on the pulse shape of input light, we utilize scintillation light itself by illuminating plastic scintillators by a N$_2$ laser with the intensity is controlled by ND filters appropriate for the given dynamic range. The N$_2$ laser (KEN-1020) produces an intense fast laser pulse of several 100 psec of wave length of 337 nm. Since fast laser photons directly illuminate the color centers of a wave length shifter, the light emission time profile is similar to the one produced by MIPS. These light pulses are easily attenuated by a factor of 1 to $10^{-5}$ with variable ND filters. The absolute light yield from a scintillator for 1 MIP can be calibrated by cosmic ray muons or by a $\beta$ source. Linearity of all the PMTs for the plastic scintillator layers will be checked by this procedure for a range of $10^2$-$10^3$ MIPs. Relative gain adjustment among the PMTs will also be done.

3.7.2 Calibration by CERN SPS beam test

In a forthcoming test beam experiment at CERN in 2006, the LHCf calorimeters will be exposed to a muon beam and high energy electron and proton beams to calibrate their absolute energy scale and position dependence. When the calorimeter is exposed to the muon beam (single MIP), a higher voltage of 1kV will be applied to the PMTs in order to obtain $10^3$ gain. The output signal is again amplified by a pre-amplifier of 10~100 gain to detect a single MIP level signal. Recording the ADC counts for a single MIP for all the scintillator layers then gives an absolute by calibration of each layer. Measurement will be done for several incident beam positions in order to calibrate the position dependence of the photon collection from the scintillators. These data will be used for alignment calibration of the position sensitive layers.

The calorimeters will be exposed to a high energy electron beam up to 250 GeV. In this measurement the PMT and pre-amplifier gains will be set exactly as the real LHCf experiment. Then we will check the absolute energy scale, position dependence, energy resolution, position reconstruction, $\gamma$/hadron separation and so on. These data are also cross-checked with a Monte Carlo calculation and used to evaluate systematic errors.

3.7.3 Run-time calibration

During the LHCf run-time possible degradation of the scintillation yield or PMT gain may happen. In order to track relative changes of the energy scale, N$_2$ laser light produced by a similar system to the one described above will be distributed to the scintillator layers. The laser system will be placed in the USA15 area or its neighbouring sight so it is accessible. The laser light is transmitted 200m to the LHCf calorimeters by a single quartz fiber. Drift of the overall response of the PMTs will be occasionally monitored.
Another strong calibration tool for the energy scale is the reconstructed $\pi^0$ invariant mass peak in the sample with hits in both calorimeters of either Detector #1 or #2. A typical mass resolution of $\sim5\%$ will provide a useful and accurate constraint on drift of the energy scale.
4 LHCf Simulations and physics performance

4.1 Expected performance of detector

4.1.1 Optimization of the longitudinal geometry and expected performances

A simulation of the sampling tungsten/scintillator calorimeter with the Si detector inserted in between has been developed by means of the FLUKA packages. In order to choose the best configuration, several geometrical arrangements have been studied. As an example, Figure 35 shows an electromagnetic shower produced by a 500 GeV photon with a calorimeter composed by 2 towers and 4 double layers of Si detectors inserted at 0, 8, 10 and 38 radiation lengths.

The detector spatial resolution (i.e. the precision in the photon impact point measurement) has been evaluated as function of the incident photon position on the Si sensor. Figure 36 shows the spatial resolution as function of the depth for several photon energies ranging from 56 GeV to 1800 GeV, without taking into account saturation effects of the preamplifiers.

To study the efficiency of the Si detectors, an energy deposition threshold of about 200 MIPs has been assumed to make a good position reconstruction. Based on this 200 MIPs threshold, Figure 37 shows the position detection efficiency for different energies as a function of the depth. To maximize the spatial resolution and the detection efficiency in the whole energy range, we decided to install two pairs of Si detectors (each one composed of X and Y view) at 6 and 10 radiation lengths. Another two pairs are located in front of the calorimeter (to detect and distinguish all the charged particles incident on the detectors) and at 38 r.l. (to measure the position of the shower produced by neutrons).

It must be pointed out that the resolution reported in Figure 36 is estimated in the case that every strip is read out (80 μm pitch) and for a geometric configuration without air gaps in front of and behind the silicon detectors. Figure 38 shows the spatial resolution obtained when every other strip is read out, compared with the ideal case. The worsening of the resolution has been considered acceptable considering the corresponding gain in the number of electronic channels.

An air gap in front of the silicon detector spoils the spatial resolution because in that gap the particle spatial distribution is broadened without any new particle production. This effect has been studied by means of the simulation: for example, with the introduction of 1 cm of air the resolution worsens from 20 μm to 83 μm for a detector at 10 r.l. measuring photons at 560 GeV. From the simulation studies an air gap of 1.5 mm is acceptable when the LHC tunnel is closed.
Figure 35: Simulation of a 500 GeV induced photon shower. In this example the detector is composed of a tower of two calorimeters (2.5 × 2.5 cm² and 3.5 × 3.5 cm²) and 8 Si detectors of 285 μm thickness inserted at 0, 8, 10 and 38 r.l..
Figure 36: Spatial resolution of the Si detector for the photon impact point measurement for different photon energies, as function of the depth (expressed in units of radiation length).
Figure 37: Efficiency of the Si detectors in the photon impact point measurement for different energies as function of the depth in units of radiation length.

Finally, a study of the spatial resolution obtainable taking into account the saturation effect of the pre-amplifiers has been done. The chosen pre-amplifiers (PACE3 chips, described in detail in Section 3.4) are perfectly linear up to 1.4 pC input charge, with a non-linearity smaller than 6% for input charges up to 2 pC (corresponding approximately to 600 MIPs, or 45 MeV energy loss in 300 μm thick Si sensors). Figure 39 shows the expected transverse profile at 6 X_0 for a 1 TeV photon. Since the saturation effect is present only in the very center of the shower, that is very narrow (≤ few strips at 160 μm pitch), the expected effect on the spatial resolution is small. This is demonstrated in Figure 40, that shows the distribution of the residuals between the impact point at the generator level and the reconstructed impact point for 1 TeV photons at 6 r.l.; in the upper plot the saturation effect is not taken into account, while in the lower one the saturation is included. The difference in the spatial resolution is practically negligible (from 15 μm to 16 μm).
Figure 38: Spatial resolution for the 1000 GeV photon impact point when every strip is read out (black points) and when every other strip is read out (red points).
Figure 39: Example of a transverse profile in the Si sensor at 6 r.l. for a 1 TeV photon; in the upper figure the saturation effect of the preamplifier is not taken into account, while in the lower one the saturation is included (600 MIP dynamic range).
Figure 40: Distribution of the residuals between the impact point at the generator level and the reconstructed impact pointe for 1 TeV photons at 6 r.l.; in the upper plot the saturation effect of the preamplifier is not taken into account, while in the lower one the saturation is included.

4.2 Expected physics performance

4.2.1 Monte Carlo setup for this study

Here we discuss a study of the expected physics performance of the Detector #1. The Monte Carlo code used for the detector simulation was EPICS [26], which has been tested against various experimental results. It has also been compared with other Monte Carlo codes and proven to give almost identical results as EGS4 for simulations like the present work. It can also simulate hadronic interactions and proven to give good results when compared with CERN test beam results [27].

The hadronic interaction models used are DPMJET3 and QGSJET-II. The code, DPMJET3 [28], can be used at energies as low as the multi-particle production threshold to the $10^{20}$ eV region, and includes PYTHIA and PHOJET as its ingredients. As mentioned above it gives good results for beam tests and also is the best among various codes for
explaining the cosmic ray observations for which the primary cosmic ray spectrum is well known [24, 29].

QGSJET-II [30] is an updated version of QGSJETI which has been widely used in the simulation of cosmic ray phenomena. The SIBYLL code is also a popular code for simulating cosmic ray phenomena. We have also employed QGSJETI and SIBYLL as particle interaction generators.

In the current simulation, we set the minimum kinetic energy cut to be 100 keV. During the particle tracking we took into account the precise magnetic dipole field of D1 inside the beam pipe.

We are also trying to introduce standard Monte Carlo sets commonly used in high energy physics such as GEANT4 and PYTHIA.

4.2.2 Overview

At the position of LHCf detector, most of the charged particles from the interaction region have been deflected by forward magnets so that only neutral particles such as γ's from π⁰ decays, neutrons or neutral kaons reach the detector. Figure 41 shows the position distribution of γ's at the detector plane about 140m apart from the collision point. The flux is mostly concentrated within a few cm around the center of the neutral particle flux arriving from the IP, which is the direction of the proton beam at collision projected to the detector plane.

Fig. 42 shows the E_γ-P_T,γ correlation plot of photons. The curve shows the P_T acceptance defined by the vertical aperture of the beam pipe in the D1 magnet. The upper and the lower curves correspond to the beam crossing angles of 140 µrad. and 0 µrad., respectively. The photons that fall in the area under the curves will be detected by LHCf. From these curves it can be seen that almost all photons with energies higher than ~2 TeV can be detected by LHCf.
Figure 41: The flux of photons per inelastic interaction is shown as a function of x-y position in the detector plane.

Figure 42: The $E_\gamma$-$P_{T_\gamma}$ correlation plot. High energy photons with small $P_{T_\gamma}$ can be recorded by the LHCF shower counter. The curves show geometrical cuts for our shower calorimeter arising from the configuration of the beam pipe and magnets. The upper curve (red) and the lower curve (green) correspond to beam crossing angles of 140 $\mu$rad and 0 $\mu$rad, respectively.

Fig. 43 and Fig. 44 show the $X_F$ distribution with different $P_T$ cuts for the beam
crossing angles of 0 μrad. and 140 μrad., respectively. In the case of 0 μrad for beam crossing angle, the region with \( P_T < 0.5 \) gives 66% efficiency for the \( \gamma \) in the region of \( X_F > \sim 0.3 \). Fig. 45 shows the energy acceptance of detected \( \gamma \)'s limited by the beam-pipe aperture. Almost all photons with \( E_\gamma > 2 \) TeV, can be detected.

With zero degree crossing angle the 2cm\( \times \)2cm tower of the Detector #1 is placed at the center of the flux of neutral particles from the IP. In this case, about half of the 4cm\( \times \)4cm calorimeter will be cut off by the beam-pipe aperture as shown in Fig 15. As for the Detector #2, the center of 2.5cm\( \times \)2.5cm tower is shifted downward and sideway from the center of the beam-pipe by 0.4 cm in each direction as shown in Fig. 16.

![Graph](image_url)

**Figure 43:** The production spectra of secondary particles are shown as functions of \( E_\gamma \) and \( P_{T,\gamma} \). Each curve on the histogram represents the measured \( X_F \) region of interest for the corresponding \( P_T \) region. For example, for \( \gamma \)'s in the region of \( X_F > \sim 0.3 \), \( P_T \) acceptance with \( P_T < 0.5 \) GeV/c gives 66% efficiency. Here no crossing angle is assumed.
Figure 44: The production spectra of secondary particles are shown as functions of $E_\gamma$ and $P_{T_\gamma}$. The description is the same as the previous plot. Here 140 $\mu$rad crossing angle is assumed.

As shown in Fig 46, approximately 20% of the total photon events will have two photons in the same tower. We propose to select such data during data analysis by using the SciFi and Si detectors to identify multiple shower centers. 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.

Most of the background causing energy contamination comes from secondary particles interacting with the beam-pipe. The flux of such particles is large but they are concentrated at low energy, typically below 20 GeV, and have limited impact on the energy measurement of showers by $\gamma$’s with energy $>100$ GeV. Therefore we do not take into account the beam pipe material in further Monte Carlo studies reported in this section. For simplicity, here we define “one event as an event” that fulfill the following conditions: 1.) the leading particle has energy $>100$ GeV and 2.1) the second most energetic particle has $<10\%$ of energy of the leading particle, or 2.2) the distance between the leading and the second most energetic particles is $<5$mm at the detector plane.
Figure 45: The $\gamma$ energy distribution with and without the acceptance limited by geometrical $P_T$ cut due to the aperture of the beam-pipe. The top histogram shows the energy spectrum without the acceptance $P_T$ cut. The two other histograms include $P_T$ cuts for photons with emission angle $>450$ $\mu$rad (for Detector #1 with 140 $\mu$rad crossing angle) and $>310$ $\mu$rad (for Detector #1 with 0 $\mu$rad crossing angle).

Figure 46: The effect of multiple hits of photons in the 2cm x 2cm calorimeter of Detector #1 located at the centerline of the beam-pipe. The plot on the left shows energy contaminations. The plot on the right shows energy contamination versus photon energy of the leading photon from 100 GeV to 5 TeV. The rate of events with more than 5% contamination is about 20%. Most of the contamination comes from low energy photons with energy less than 20 GeV.
The multiplicity of “events” at each calorimeter with zero degree crossing angle and the detectors positioned as shown in Fig. 15 is shown in Fig. 47 for the Detector #1 and #2. Here a large fraction of the multiplicity = 2 events come from high energy \( \pi^0 \) decays with narrow opening angles. About 70\% and 40\% of the multiplicity=2 events at the 2cm×2cm and the 4cm×4cm towers of Detector #1 come from such \( \pi^0 \)'s.

Figure 47: The multiplicity distribution for each calorimeter of Detector #1 (upper plot) and Detector #2 (lower plot). See the text for the definition of “multiplicity”. The vertical axes correspond to the number of “events” per inelastic collision.
Figure 48: The $\gamma$ energy resolution for the 2cm x 2cm calorimeter of Detector #1. At 1 TeV the resolution is 3%.

Typical acceptance for the default configuration is summarized in Tab. 3 and in Tab. 4 for the Detector #1 with 0 $\mu$rad. and 140$\mu$rad. beam crossing angles, respectively. Tab. 5 also shows the event rate for the Detector #2 at the default position. At the default position of the Detector #1, the event rates for the particles with $>100$ GeV are about 0.067 and 0.047 per inelastic collision at the 2cm x 2cm tower and at the the 4cm x 4cm tower, respectively. In this case 0.045 $\gamma$'s and 0.015 hadrons hit the 2cm x 2cm tower per inelastic collision.

In order to reconstruct energy correctly, we require the entering position of 2mm inside the edge of a calorimeter. The efficiency of the 2mm fiducial cut is about 60% for $\gamma$ events. 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
Table 3: Event rate of single $\gamma$’s and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of beam-pipe and without beam crossing angle.

<table>
<thead>
<tr>
<th></th>
<th>20mm x 20mm</th>
<th>40mm x 40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sum E &gt; 100GeV</td>
<td>0.0674</td>
<td>0.0465</td>
</tr>
<tr>
<td>2. One Gamma Incident</td>
<td>0.0478</td>
<td>0.0353</td>
</tr>
<tr>
<td>3. One Hadron Incident</td>
<td>0.0146</td>
<td>0.0052</td>
</tr>
<tr>
<td>4. One Gamma in fiducial</td>
<td>0.0297</td>
<td>0.0272</td>
</tr>
<tr>
<td>5. One Neutron in fiducial</td>
<td>0.0006</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Table 4: Event rate of single $\gamma$’s and hadrons per inelastic collision for the Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and with beam crossing angle of 140μrad.

<table>
<thead>
<tr>
<th></th>
<th>20mm × 20mm</th>
<th>40mm × 40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sum E &gt; 100GeV</td>
<td>0.0674</td>
<td>0.0869</td>
</tr>
<tr>
<td>2. One Gamma Incident</td>
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<td>0.0623</td>
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<tr>
<td>3. One Hadron Incident</td>
<td>0.0145</td>
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<tr>
<td>4. One Gamma in fiducial</td>
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<td>0.0511</td>
</tr>
<tr>
<td>5. One Neutron in fiducial</td>
<td>0.0006</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Table 5: Event rate of single $\gamma$’s and hadrons per inelastic collision for the Detector #2. Here the detector is at default position and without beam crossing angle.

<table>
<thead>
<tr>
<th></th>
<th>20mm × 20mm</th>
<th>40mm × 40mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sum E &gt; 100GeV</td>
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<td>0.0721</td>
</tr>
<tr>
<td>2. One Gamma Incident</td>
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<td>3. One Hadron Incident</td>
<td>0.0198</td>
<td>0.0078</td>
</tr>
<tr>
<td>4. One Gamma in fiducial</td>
<td>0.0445</td>
<td>0.0427</td>
</tr>
<tr>
<td>5. One Neutron in fiducial</td>
<td>0.0009</td>
<td>0.0002</td>
</tr>
</tbody>
</table>
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. 48 as a function of photon energy.

For accurate energy reconstruction of hadron events, events which starts their shower development near the front of the detector need to be selected. In addition to the fiducial cut for entering position, we require the energy deposited in the first r.l. is >20 MIPs. The efficiency of this cut is about 4%. Fig. 50 shows ~30% energy resolution of LHCf for 6TeV neutrons with above cut. With this experiment we will have the possibility of measuring the in-elasticity K.

![Invariant Mass](image)

Figure 49: Simulation of the two photon invariant mass distribution for the 2cm×2cm calorimeter at the zero degree. The 5% energy resolution and 200 μm position resolution for photons are taken into account in this plot.
Figure 50: The energy resolution of neutrons with 6 TeV. The events selected have showers starting in the first r.l. with > 20 MIPs. The fraction of neutrons satisfying this condition is 4.1%. The horizontal axis represents the number of shower particles in the nuclear cascade. The neutron showers that are selected are required to have their impact point 2mm inside the calorimeter edge.

Next we discuss position resolution. We have evaluated the expected position resolution for photons of different energies in Detector #1 by using Monte Carlo calculations. For example, the expected position resolution is 160 μm for 2 TeV photons incident on Detector #1. The position of neutrons can be determined with similar accuracy, for example 170 μm for 1 TeV neutrons.

The π⁰ mass can be reconstructed in the invariant mass distribution of two γ’s, one each hitting the two tower calorimeters of Detector #1 or Detector #2. Figure 49 shows the invariant mass distribution of two γ’s for the Detector #1. We expect about 5% for mass resolution taking into account 5% energy resolution and 200μm for spatial resolution. The neutral pion mass peak can be used for the absolute calibration of energy scale.

The acceptance for π⁰ detection at the Detector #1 is summarized in Tab. 6 and Tab. 7 for 0μrad and 140μrad beam crossing angle, respectively. The 2cm×2cm calorimeter is placed at the center of the flux of incident photons and neutrons for each case. Tab. 8 also shows π⁰ acceptance for Detector #2 at the center of neutral particle flux with zero beam crossing angle. Typically ~10⁻³ π⁰ can be collected for one inelastic collision.

In Figures 51 and 52 the geometrical acceptances for single γ events and for π⁰ → γγ events are shown. In the first case the acceptance is drawn as a function of the distance between the beam line and the impact point of the particle on LHCf. In the latter case,
considering that we have two \(\gamma\)'s hitting the two different calorimeters, the acceptance is shown as a function of the distance between the beam line and the impact point defined by extrapolating the pion trajectory at production.

![Graph](image)

Figure 51: Geometrical acceptance of Detector #1 (solid blue) and # 2 (dotted red) for single \(\gamma\) events as function of the distance from the beam axis.
Figure 52: Geometrical acceptance of Detector #1 (the upper plot) and #2 (the bottom plot) for π⁰ fully reconstructed in the calorimeter (i.e. with both photons detected, one photon in each calorimeter); the acceptance is plotted as function of the distance between the beam line and the extrapolated impact point of the pion on the detector. Results are plotted for different π⁰ energies.
| 1. One Particle Incident on each Calorimeter | 0.0040 |
| 2. Gamma Incident on each Calorimeter | 0.0032 |
| 3. Invariant mass cut (125 MeV < M_{\gamma\gamma} < 145MeV) | 0.0007 |

Table 6: Event rate of $\pi^0$ production per inelastic collision for Detector #1. Here the 2cm×2cm calorimeter is at the center of beam-pipe and the beam crossing angle is zero.

| 1. One Particle Incident on each Calorimeter | 0.0066 |
| 2. Gamma Incident on each Calorimeter | 0.0052 |
| 3. Invariant mass cut (125 MeV < M_{\gamma\gamma} < 145MeV) | 0.0011 |

Table 7: Event rate of $\pi^0$ production per inelastic collision for Detector #1. Here the 2cm×2cm tower is at the center of the neutral particle flux and the beam crossing angle is 140$\mu$rad.

| 1. One Particle Incident on each Calorimeter | 0.0080 |
| 2. Gamma Incident on each Calorimeter | 0.0063 |
| 3. Invariant mass cut (125 MeV < M_{\gamma\gamma} < 145MeV) | 0.0015 |

Table 8: Event rate of $\pi^0$ production per inelastic collision for Detector #2. Here the 2.5cm×2.5cm calorimeter is at the center of neutral particle flux and the beam crossing angle is 0$\mu$rad.
4.2.3 LHCf discrimination between various interaction models

The single $\gamma$ sample  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 for high energy cosmic ray physics. Among these codes, the DPMJET3, QGSJET, QGSJET-II and SIBYLL models are tested. Figure 53 shows energy distribution of single $\gamma$ events for the 2cm×2cm calorimeter of Detector #1 at the center of the neutral particle flux. Here event multiplicity defined above is one and $\gamma$’s in the fiducial ( 2mm inside from the calorimeter edge) are selected. Instead of detailed detector simulations, we simply smear the distribution by the energy resolution of detector. As shown in Fig 53, the SIBYLL model gives lower yield than other models by about a factor of 2. The DPMJET model gives slightly higher yield than the QGSJET-II model. By measurement of inclusive $\gamma$ cross-section with reasonable accuracy, we can discriminate the SIBYLL model from others. We also tested discrimination based only on the differences in the shape of energy spectra. Here we defined the $\chi^2$ as,

$$
\chi^2_i(\alpha, \beta) = \sum_i \frac{(\alpha N_i^{data}(\beta) - N_i^{model})^2}{(\sigma_i^{data})^2 + (\sigma_i^{model})^2}
$$

where $N_i^{data}(\beta) = N(\beta E_\gamma)$ is i-th bin of the energy spectrum of $\gamma$’s scaled by factor of $\beta$ for a reference model (QGSJET-II), $N_i^{model} = N(E_\gamma)$ is i-th bin of energy spectrum of $\gamma$’s for tested models (QGSJET, DPMJET3 and SIBYLL), $\alpha$ is a normalization factor, $\beta$ is a scale factor for the energy scale, $\sigma_i^{data}$ and $\sigma_i^{model}$ are statistical errors of the i-th bin for the reference model and the tested model, respectively. Here we conservatively set $\alpha$ and $\beta$ as free parameters. We use $4\times10^5$ Monte Carlo events of the QGSJET-II model for the reference model and $9\times10^5$ Monte Carlo events for each of the tested models. Figure 54 shows the comparison of QGSJET-II and SIBYLL energy spectrum shape after minimization of $\chi^2$. The SIBYLL model gives a rather softer spectrum for the high energy $\gamma$’s than that from the QGSJET-II model. The minimum-$\chi^2$ values obtained for the QGSJET, DPMJET3 and SIBYLL models are $\chi^2=58$, $\chi^2=73$ and $\chi^2=135$, respectively with DOF=67. Therefore the SIBYLL model can be discriminated against the other two models by such a shape analysis.
Figure 53: The difference in the $\gamma$ energy distributions of QGSJET, QGSJET-II DPMJET3 and SIBYLL models. Here 5% energy resolution is assumed. Discrimination between the QGSJET and SIBYLL models is possible.
Figure 54: Shape comparison of the $\gamma$ energy distributions predicted by the QGSJET model version II and SIBYLL model. Here $5\%$ energy resolution is assumed. The left histogram is for the $2\text{cm}\times2\text{cm}$ tower at the center of the neutral particle flux. The right histogram shows for the same tower but shifted upward from the the center of the neutral particle flux by $3\text{cm}$. If we compare the photon distribution obtained at different positions of the shower detectors, discrimination between them becomes much clearer. In a similar way, the discrimination between QGSJET-II and DPMJET3 also becomes clear if we compare the spectrum at two different calorimeter positions.

However discrimination between QGSJET and the models QGSJET-II and DPMJET3 will be difficult based on data taken with the $2\text{cm}\times2\text{cm}$ calorimeter placed only at the center of the neutral particle flux. Consequently we also performed an analysis with the position of the $2\text{cm}\times2\text{cm}$ calorimeter shifted upwards $3\text{cm}$ from the center of the neutral particle flux. In order to avoid the aperture cut by the D1 beam-pipe this was accomplished with $140\mu\text{rad}$ downward crossing angle, which displaces the center of the neutral particle flux downward by $2\text{cm}$, and physically moving the $2\text{cm}\times2\text{cm}$ calorimeter upward by $1\text{cm}$.

We minimized the following combined $\chi^2$ as;

$$\chi^2_{1+2}(\alpha_1, \alpha_2, \beta) = \chi^2_1(\alpha_1, \beta) + \chi^2_2(\alpha_2, \beta)$$

(2)
where $\chi^2_1$ and $\chi^2_2$ are the $\chi^2$ functions for the 2cm×2cm calorimeter at the center of the neutral particle flux and 3cm above the center, respectively. Here $\alpha_1$ and $\alpha_2$ are normalization parameters for each detector position. We use a common $\beta$ for the two position, since the same 2cm×2cm calorimeter is used. Again we conservatively set $\alpha_1$, $\alpha_2$ and $\beta$ as free parameters. The $\chi^2_{1+2}$'s obtained for the QGSJET model, DPMJET3 and SIBYLL models are $\chi^2_{1+2}=107$, $\chi^2_{1+2}=224$ and $\chi^2_{1+2}=816$, respectively with DOF=125.

Therefore the combination of measurements with the 2cm×2cm detector at different vertical positions with respect to the center of the neutral particle flux gives better discrimination, particularly between the QGSJET-II and DPMJET3 models.

**The $\pi^0$ sample**  As we discussed a clean $\pi^0$ sample can be obtained from the invariant mass distribution of the two $\gamma$ sample. The $\pi^0$ sample is more robust than the single $\gamma$ sample against background from beam-gas or other sources thanks to the kinematical constraint. Here we discuss the model discrimination power of the $\pi^0$ sample. Figure 55 shows the $\pi^0$ energy distribution for three different interaction models, QGSJET-II, DPMJET3 and SIBYLL. With similar to the case of the single $\gamma$ sample, the $\pi^0$ yield for the SIBYLL model is about a half of other models. In the $\pi^0$ sample, the energy spectrum for the DPMJET3 model gives a harder spectrum than that for the QGSJET-II model. Detailed $\chi^2$ analysis is now under way in order to address the model discrimination power more quantitatively.

**Figure 55**: The $\pi^0$ energy distributions are shown for the QGSJET-II, DPMJET3 and SIBYLL models. The $\pi_0$ energy resolution is 5% and the $\gamma$ position resolution is 200 $\mu$m.
The neutron sample The neutron sample gives more discrimination between the models than the $\gamma$ and $\pi^0$ samples. Figure 56 shows the true neutron energy spectra incident on the 2cm×2cm calorimeter for the various models. The 2cm×2cm calorimeter is placed at the center of the neutral flux. There are significant differences between the models QGSJET, QGSJET-II, DPMJET3 and SIBYLL. Figure 57 shows the energy spectra measured by LHCf taking into account 30% energy resolution. Even with 30% energy resolution there are significant differences between the models. Below 3 TeV contamination by neutral kaons becomes significant therefore we will restrict the neutron analysis to events $> 3$ TeV which still covers a significant part of the spectrum.

Thus our experiment is very important for the discrimination between the 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.

![Neutron Energy Spectrum of 20mm square at beam center](image)

Figure 56: The energy distribution of neutrons incident on the 2cm×2cm calorimeter for various models. The calorimeter is positioned at the center of the neutron flux.
Figure 57: The neutron energy spectra expected to be measured by LHCf for the conditions of Fig 50. An energy resolution of 30% has been applied by simple Gaussian smearing of the spectra in Figfigneut-res which leads to the tails extending above the 7 TeV proton energy of LHC.

4.2.4 Double arm physics

Double arm coincidence measurement could provide useful constraints to Monte Carlo models. For example, double arm tagging of neutron $+$π$^0$ events may help constrain the models. These types of measurement also provide interesting results in forward physics at TeV energy. The physics capability of double arm coincidences has not yet been done.

4.3 Event rate and background estimation

4.3.1 Event rate for beam-beam collisions

The rate of pp collisions in LHC is

$$R_{pp} = L \cdot \sigma_{pp} = f_{rev} \frac{\gamma M N_b^2}{4\pi \beta^* \varepsilon_N} \sigma_{pp}$$

where $f_{rev}$ is the revolution frequency, $\gamma$ is the relativistic gamma, $M$ is the number of bunches, $N_b$ is the number of protons per bunch, $\beta^*$ is the lattice focusing function at the IP, $\varepsilon_N$ is the normalized beam emittance and $\sigma_{pp}$ is the inelastic pp cross-section. Table 9 summarizes the various LHC parameters that are needed for calculation.
# Table 9: LHC parameters

For the LHCf case, M is required to be less than 43 in order to prevent event pile up in 2μsec. We also want to avoid multiple pp events per bunch crossing. If we require the probability of two or more pp interactions per bunch crossing be less than 1% then the luminosity per bunch must be less than \( \sim 2 \times 10^{28} \text{cm}^{-2} \text{s}^{-1} \). In this case, luminosity with 43 bunches becomes \( \sim 8.6 \times 10^{29} \text{cm}^{-2} \text{s}^{-1} \). At this luminosity the pp interaction rate is \( \sim 70 \text{kHz} \), corresponding to \( \sim 0.1 \) interaction per crossing. There is no special choice for \( \beta^* \) and \( N_b \) if luminosity per bunch meets this level. However in order to maximize S/N ratio for given beam-gas background, smaller \( \beta^* \) has advantage because smaller \( \beta^* \) can increase only the beam-beam event rate without changing beam-gas event rate. For the calculation of event rates and run times need by LHCf we uses the rates given in Tab 3 to Tab 5. Tab.s 10 to 12 show the event rates and typical running times in the case of \( 10^{29} \text{cm}^{-2} \text{s}^{-1} \) luminosity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{rev}(Hz) )</td>
<td>( 11.2 \times 10^3 )</td>
</tr>
<tr>
<td>( e_N ) (μm-rad)</td>
<td>3.75</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>7461</td>
</tr>
<tr>
<td>( \sigma_{pp} ) (mb)</td>
<td>80</td>
</tr>
<tr>
<td>D (m)</td>
<td>80</td>
</tr>
</tbody>
</table>

# Table 10: Event rate and run-time for 1% statistics with typical luminosity of \( 10^{29} \text{cm}^{-2} \text{s}^{-1} \) at the Detector #1. Here the 2cm x 2cm tower is at the center of beam-pipe and the beam crossing angle is zero.

<table>
<thead>
<tr>
<th>Rate [1/sec]</th>
<th>( \gamma )</th>
<th>( \pi^0 )</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate [1/sec]</td>
<td>489.3</td>
<td>5.6</td>
<td>5.8</td>
</tr>
<tr>
<td>time of 10,000 events [min]</td>
<td>0.34</td>
<td>29.5</td>
<td>28.7</td>
</tr>
</tbody>
</table>

# Table 11: Event rate and run-time for 1% statistics with typical luminosity of \( 10^{29} \text{cm}^{-2} \text{s}^{-1} \) at the Detector #1. Here the 2cm x 2cm tower is at the center of the neutral particle flux and the beam crossing angle is 140μrad.

<table>
<thead>
<tr>
<th>Rate [1/sec]</th>
<th>( \gamma )</th>
<th>( \pi^0 )</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate [1/sec]</td>
<td>489.3</td>
<td>8.5</td>
<td>6.2</td>
</tr>
<tr>
<td>Time for 10,000 events [min]</td>
<td>0.34</td>
<td>19.6</td>
<td>27.0</td>
</tr>
</tbody>
</table>

## 4.3.2 Background from beam-gas interactions

The beam-gas background is due to collisions between the beam and the residual gas molecules inside the beam-pipe. If a gas species \( j \) is present in the interaction region over
Table 12: Event rate and run-time for 1% statistics with typical luminosity of $10^{30}\text{cm}^{-2}\text{s}^{-1}$ at the Detector #2. Here the Detector is at the center of the neutral particle flux and the beam crossing angle is zero.

A length of beam tube D with density $n_j$ the rate of beam-gas collisions is

$$R_{pj} = f_{rev} M N_b D n_j \sigma_{pj}$$  \hspace{1cm} (4)

where $\sigma_{pj}$ is the beam-gas collision cross-section. From Ref. 18 the length of beam tube in the interaction region with highest pressure is in the location of the Q1-Q3 quadrupoles and DFBX from $\sim 20-60\text{m}$ on both sides of the IP, so $D \sim 2\times40 = 80\text{m}$. Beam-gas interactions between D1 and LHCf are neglected since collision fragments from these will be centered on the out-going beam pipe rather than LHCf. Beam gas interactions from the beam approaching from the back of the TAN are also neglected since these will be absorbed by the TAN shielding that is behind LHCf. As a worst case it is assumed that beam-gas events generate LHCf triggers with the same efficiency as pp collisions. Eqn. 4 summed over gas species and divided by Eqn. 3 then gives the ratio of beam-gas events to pp events and we clearly want this to be a small number. This ratio is

$$\frac{\sum_j R_{pj}}{R_{pp}} = \frac{4\pi \beta \epsilon_N}{\gamma N_b} \sum_j \frac{D n_j \sigma_{pj}}{\sigma_{pp}}$$

$$= \frac{4\pi \beta \epsilon_N}{\gamma N_b} D n_{H_2,\text{equiv}}$$  \hspace{1cm} (5)

where the $H_2$ equivalent density is defined as

$$n_{H_2,\text{equiv}} = \sum_j \frac{n_j \sigma_{pj}}{\sigma_{pp}}$$  \hspace{1cm} (6)

Table 13 gives beam-gas nuclear cross-sections. In Tab. 14 the beam-gas collision rate normalized to the pp event rate is given for luminosities and bunch numbers $M$ of interest to LHCf. The first two entries are for 43 bunches, $\beta^* = 1$ and $18\text{m}$ and the bunch intensity at the upper limit for the probability of two or more interactions per bunch crossing being less than 1%. For gas density we have taken an $H_2$ equivalent density equal to $4\times10^{12}H_2/\text{m}^3$ from Fig. 4a in ref 18 for machine start-up conditions. This is a conservative upper bound because the gas density in this Fig. was calculated for 43 bunches with bunch intensity $1.1\times10^{11}\text{cm}^{-2}\text{s}^{-1}$ which exceeds the upper bound for LHCf by a factor 11 (for $\beta^* = 1\text{m}$) and 2.3 (for $\beta^* = 18\text{m}$). Nevertheless we see from Table 14 that the ratio of beam-gas to pp interactions is very small for these two cases, $2\times10^{-4}$ and $8.4\times10^{-4}$ respectively. Four additional cases are given in Table 14 for luminosity
10^{28}\text{cm}^{-2}\text{s}^{-1}, 43 or 8 bunches and $\beta^* = 1$ or 18m. In the worst case the ratio of beam-gas to pp interactions is $7.5 \times 10^{-3}$ and negligible.

We therefore conclude from Table 14 that, within the state of current knowledge of LHC vacuum conditions, beam-gas interactions are negligible for LHCf operations.

<table>
<thead>
<tr>
<th>j</th>
<th>$\sigma_{pj}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>100</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>600</td>
</tr>
<tr>
<td>CO</td>
<td>810</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1220</td>
</tr>
</tbody>
</table>

Table 13: Beam-gas nuclear cross-sections

<table>
<thead>
<tr>
<th>Luminosity (cm$^{-2}$s$^{-1}$)</th>
<th>$\beta^*$ (m)</th>
<th>M</th>
<th>$N_b$</th>
<th>$I_b$ (mA)</th>
<th>$\sum R_{pj}/R_{pp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8 \times 10^{25}$</td>
<td>1</td>
<td>43</td>
<td>$1 \times 10^{10}$</td>
<td>0.791</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>$8 \times 10^{25}$</td>
<td>18</td>
<td>43</td>
<td>$4.3 \times 10^{10}$</td>
<td>3.355</td>
<td>$8.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$1 \times 10^{25}$</td>
<td>1</td>
<td>43</td>
<td>$1.1 \times 10^{9}$</td>
<td>0.088</td>
<td>$1.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$1 \times 10^{25}$</td>
<td>18</td>
<td>43</td>
<td>$4.8 \times 10^{9}$</td>
<td>0.375</td>
<td>$7.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$1 \times 10^{25}$</td>
<td>1</td>
<td>8</td>
<td>$2.6 \times 10^{8}$</td>
<td>0.038</td>
<td>$7.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$1 \times 10^{25}$</td>
<td>18</td>
<td>8</td>
<td>$1.1 \times 10^{10}$</td>
<td>0.162</td>
<td>$3.2 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 14: Beam-gas event rates

4.3.3 Background from secondary particle collisions with the beam-pipe

This background is produced by the secondary particles from beam-beam collisions interacting with the beam pipe. When the charged secondary particles (protons and charged pions and kaons) and/or neutral particles (photons, neutrons and neutral kaons) pass through the beam pipe, they will make electromagnetic and nuclear interactions and/or cascade showers inside the beam pipe. Those particles emitted inside the beam pipe between the D1 magnet and the TAN can enter the detector as the background. The effect has been estimated by using the DPMJET model. The results shown in Fig. 58 tells us that the main background consists of very low energy photons with energy between 10 keV and 10 GeV. Beyond 100GeV, the flux decreases and over 350 GeV ($X_F \sim 0.05$), the S/N ratio is estimated as 140 or the N/S ratio is 0.007. So the background from secondary particle collisions with the beam-pipe will not be a problem for LHCf.
Figure 58: Background energy fluence at the 2cm×2cm calorimeter from the interaction of secondary particles with the beam-pipe. The energy fluence of photons from IP interactions is also shown for comparison. Data are shown for radial bands 0—2cm and 2—4cm from the beam-pipe axis. Photons from the IP dominate above 100 GeV.

4.3.4 Background from beam-halo interaction with the beam-pipe

It is possible beam halo protons may hit beam-pipe aperture in the interaction region and cause background events in the LHCf detectors. Here we make a rough estimation to derive a conservative upper-limit for amount of beam-halo. Typical beam loss rate is expected as 10^9/sec for 10^{34}cm^{-2}s^{-1} luminosity. We assume here that all the lost protons are from the beam halo and that the lost beam will be scraped at the beam cleaning insertion with a cleaning in-efficiency of 1/4000 = 2.5×10^5. We assume that all the protons missing the beam cleaning collimators will be lost in a beam-pipe aperture in IR1 and give a detectable event in LHCf with the same efficiency as pp interactions at the IP, which of course is a very conservative assumption. Scaling to the luminosity 10^{29}cm^{-2}s^{-1} for the LHCf run, which is 5 orders of magnitude lower than the nominal LHC design luminosity we calculate a beam-halo background rate for the LHCf case as 2.5×10^5/10^5 ∼ 2.5 events/s. Here we have assumed that beam-halo generation is dominated by non-linear beam-beam interactions and scales linearly with luminosity. Even if the beam-halo generation is only proportional to the total number of protons in a single beam (=M*N_b) the beam-halo rate is reduced by a minimum factor of (2808/43)*(10^{11}/4.3×10^{10}) = 152 and the beam-halo event rate would be 2.5×10^5/152 ∼ 1.6kHz. In both cases these rates are small compared to the typical pp interaction rate for LHCf conditions ∼ 8kHz at 10^{29}cm^{-2}s^{-1}. Thus beam-halo interactions with the beam-pipe will not cause a significant background event
rate in LHCf.
5 Run scenario

5.1 Overview

The first operation of LHC in colliding beam mode is envisioned with zero crossing angle and with 43 equally spaced bunches per beam (\(~2\mu\text{sec between bunches}\) [17] [19]. 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 \mu\text{sec} so events from adjacent bunches will not cause pile-up.

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 \(~2\times10^{28} \text{ cm}^{-2}\text{s}^{-1}\) or less (80mb cross section assumed). With 43 colliding bunch pairs the total luminosity would be \(8.6\times10^{29} \text{ cm}^{-2}\text{s}^{-1}\) 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 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).

Table 15 shows a plan for the LHC beam commissioning phase taken from a Chamonix talk [19]. In the early stage of “two beam physics”, the machine parameters (43 bunches, \(~10^{10} \text{ ppb}, \beta^*=18\text{m}\) will be the most desirable for LHCf.

To enlarge the range of \(P_T\) that is covered, it is desirable at some point to take data with one of the beams having a vertical crossing angle of 140\mu rad from up to down. In this case the center of neutral particle flux moves downward by about 2\text{cm} compared to zero crossing angle. Therefore the range of \(P_T\) covered is enlarged by \(~40\%\). Figure 42 shows \(E_{p}-P_{t_n}\) correlations.

Therefore we’d like to propose LHCf running in 3 phases. However the detailed strategy and run plan have not yet been finalized and will be further refined by communication and joint study with the LHC Operations and Beam Instrumentation Groups.

<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>(\beta^*) (m)</td>
<td>18</td>
</tr>
<tr>
<td>Bunch separation (\mu\text{sec})</td>
<td>2.025</td>
</tr>
<tr>
<td>Crossing angle (\mu rad)</td>
<td>0</td>
</tr>
<tr>
<td>Transverse emittance (\mu m rad.)</td>
<td>3.75</td>
</tr>
<tr>
<td>Luminosity per bunch (\text{cm}^{-2}\text{s}^{-1})</td>
<td>(~7\times10^{26})</td>
</tr>
<tr>
<td>Luminosity (\text{cm}^{-2}\text{s}^{-1})</td>
<td>(~3\times10^{28})</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>(1\times10^{10})</td>
</tr>
</tbody>
</table>

Table 15: One of typical LHC parameters in pilot luminosity phase taken from a talk at Chamonix 2006. Here the 43 bunch mode is suitable for the LHCf runs.
5.2 Phase-1: Parasitic running during LHC commissioning

Phase-1 is operation during initial beam commissioning and low luminosity running of LHC with 43 bunches per beam. Because the radiation hardness of the LHCf detectors is not sufficient for luminosity greater than $10^{30}\text{cm}^{-2}\text{s}^{-1}$, the detectors are removed when the luminosity reaches this level.

In early 2007 before closing tunnel, the LHCf detectors will be installed in the TAN. At first the detector will sit at the center of beam pipe and we will take data during single-beam running in order to estimate vacuum quality in the beam pipe by measuring beam-gas collision events.

At the beginning of two beam running at physics energy 7+7 TeV, namely “pilot run luminosity”, LHCf will take physics data in a parasitic mode. First the position of the center of neutral particles arriving at the TAN is found by measuring the position distribution of showers with position sensitive layers with accuracy of 200\(\mu\)m and 15\(\mu\)m for Detector #1 and Detector #2, respectively. 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 and first attempts would be made to measure the spectrum of shower energies, discriminate between neutron and photon induced showers and construct an invariant mass distribution for events with hits in both calorimeters of Detectors #1 and #2.

As the commissioning proceeds and the luminosity reaches $10^{29}\text{cm}^{-2}\text{s}^{-1}$ LHCf would be in full operation and the event rate would be high enough to obtain a complete data set in a few days of operation. Again throughout this period LHCf would be operating in a parasitic mode and not request special beam conditions.

Because the radiation hardness of the LHCf detectors is not sufficient for luminosity greater than $10^{30}\text{cm}^{-2}\text{s}^{-1}$, the detectors would be removed when the luminosity reaches this level. The contact dose of the LHCf detectors is conservatively expected to be less than $10^{-3}$ to $10^{-2}$ mSv/hr (30day operation at $10^{30}\text{cm}^{-2}\text{s}^{-1}$, one day cool down) and therefore not require special remote handling procedures. When the LHCf detectors are removed from the TAN they will be replaced by three Cu bar absorbers that normally fill the TAN slot in the absence of instrumentation.

5.3 Phase-2: Parasitic running with TOTEM

Phase-2 is planned when LHC operates at low luminosity $10^{28}\text{cm}^{-2}\text{s}^{-1}$ for the TOTEM experiment. LHCf proposes re-install its detectors to take data during this opportunity and would be removed upon return to luminosity $>10^{30}\text{cm}^{-2}\text{s}^{-1}$. This would have the purpose of calibrating the cross-sections measured by LHCf with the absolute luminosity measured by TOTEM and of providing an opportunity to correct some problem that may have appeared during Phase-1.

Phase-2 is planned to be a parasitic operation with the beam conditions requested by TOTEM.

It is possible that, after Phase-2 is completed with TOTEM and before removing LHCf, LHCf would request moving the position of one of its detectors and operating for a short time with 140\(\mu\)rad downward crossing angle in one beam for the purposes of extending
the range of accessible transverse momentum by 40%. The sensitivity of one of the BRAN would not be affected and therefore would provide a continuous luminosity measurement during this time.

5.4 Phase-3: Future prospects

Phase-3 is a future prospect during heavy ion runs and in the early discussion phase at the time of writing this report. In this phase, the LHCf detectors must be updated to withstand the radiation dose. If it occurs a joint experiment with ATLAS is expected during this phase.

5.5 Impact on LHC beam commissioning and luminosity monitoring

Here we describe the impact of LHCf on LHC operations, or more specifically;

1. the possible use of LHCf as a luminosity monitor during the early commissioning and operation of LHC (luminosity < \(10^{30}\) cm\(^{-2}\) s\(^{-1}\)) and

2. the effect of LHCf on the sensitivity of BRAN installed in the TAN on each side of and approximately 140m from IP1 and IP5.

5.5.1 BRAN

The BRAN are radiation hard, gas ionization chambers placed near the hadronic shower maxima in the TAN. They are designed to occupy the space of one Cu bar in the TAN instrumentation slot. In practice this means the BRAN could be installed in the position of the second, third or fourth Cu bar in the TAN slot. The BRAN are sampling calorimeters with signal proportional to the local energy deposited by neutral IP collision products and are designed to be used by LHC Operations for bringing the beams into collision and maintaining them in optimum luminosity. The BRAN therefore provide a measure of relative luminosity and are designed to be fast enough to resolve the relative luminosity of individual colliding bunch pairs at 40MHz. It is the speed of the BRAN and their relative simplicity that is their strength as a beam operations tool compared to other means of monitoring luminosity on LHC. At \(10^{29}\) cm\(^{-2}\) s\(^{-1}\) the BRAN can provide a 1% luminosity measurement in \(\sim3.6s\).

The BRAN are not absolute luminosity devices. The sensitivity of the BRAN can be calibrated in one of two ways: (1) by a raster scan of one beam through the other with simultaneous measurement of bunch intensity (van der Meer method) and (2) by simultaneously running with a physics experiment (TOTEM, ATLAS, CMS) that measures absolute luminosity. In practice it is expected that (1) would occur during the normal operational procedures for bringing the beams into collision. In addition ATLAS is planning to install a relative luminosity monitor LUCID which could be calibrated against the BRAN for the purpose of monitoring the stability of these detectors.

The installation of BRAN in both TAN of IP1 and of IP5 is for three reasons:
1. redundancy of this important measurement,

2. stability of the sensitivity of luminosity measurement when one beam is scanned through the other to find the position of optimum luminosity (the sensitivity of the BRAN facing the fixed beam is not changed),

3. measurement of the total crossing angle between the two beams.

Backgrounds due to beam-gas and beam-halo scraping are expected to be low enough that the BRAN do not need to be operated in coincidence. At very low luminosity this option is possible if needed. Operating the BRAN in coincidence would not be effective above luminosity $5 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ when there is more than one collision per bunch crossing on average.

5.5.2 Impact of LHCf Phase-1

Phase-1 is operation during initial beam commissioning and low luminosity running of LHC with 43 bunches per beam. Because the radiation hardness of the LHCf detectors is not sufficient for luminosity greater than $10^{30} \text{cm}^{-2}\text{s}^{-1}$, the detectors are removed when the luminosity reaches this level. The LHCf detectors are then replaced by three Cu bars. Because LHCf and three Cu bars are both nearly two nuclear interaction lengths thick the change in the sensitivity of the BRAN is minimized. However owing to the different transverse cross-section of the Cu bars (which fill the 9.6cm wide TAN slot) and the LHCf calorimeter plates (which for the tower centered on the beam axis is 2cm×2cm) there will be reduction in BRAN sensitivity when LHCf is installed instead of Cu bars. The reduction in BRAN sensitivity compared to Cu bars is primarily due to high-energy neutrons from the IP missing the 2cm×2cm LHCf tower calorimeter and therefore not generating a hadron shower that can be detected by the BRAN. This will reduce the BRAN counting rate by a factor of ~5 to 10 and increase the integration time for a 1% luminosity measurement from 3.6 to ~18 to 36s, still reasonably short for LHC Operations purposes. When LHCf is replaced by Cu bars it would be desirable to re-calibrate the BRAN using one of the procedures described in the preceding section.

The level-1 LHCf trigger will be bunch crossings and the level-2 trigger will be a threshold calorimeter signal, similar to the BRAN triggers. LHCf is therefore suitable for use as a luminosity monitor for luminosity $<10^{30} \text{cm}^{-2}\text{s}^{-1}$. By selecting only LHCf events that produce the $\pi^0$ invariant mass, the LHCf luminosity signal will be especially clean and free of background. The LHCf luminosity measurement should be very useful to LHC Operations during early LHC commissioning and operation for corroborating the BRAN, LUCID and other luminosity measurements. The LHCf acceptance of $\sim 10^{-3}$ for $\pi^0$ events and maximum 1kHz data rate determine the integration time for 10% luminosity measurement to be $\sim 100s$ for $L > 10^{28} \text{cm}^{-2}\text{s}^{-1}$.

5.5.3 Impact of the later phases of LHCf

Phase-2 is planned when LHC operates at low luminosity $10^{28} \text{cm}^{-2}\text{s}^{-1}$ for the TOTEM experiment. LHCf proposes reinstall its detectors to take some dedicated runs during this
opportunity and would be removed upon return to luminosity $> 10^{30}$cm$^{-2}$s$^{-1}$. It should be anticipated that between Phases 1 and 2 the activation of the Cu bars may exceed 0.1 mSv/hr contact dose and require remote handling for their removal and storage. At the end of Phase 2 and before return to high luminosity operation LHCf would be removed and replaced by three fresh Cu bars.

Phase-3 is a future prospect during heavy ion runs. In this phase, the LHCf detectors must be updated to withstand the radiation dose. A joint experiment with ATLAS is expected during this phase and it is not expected that LHCf would have an impact on LHC Operations other than those already described for Phases-1 and Phase-2.

### 5.5.4 Conclusion

LHCf is to be a parasitic operation during early Stage 1 commissioning of the LHC when the luminosity is less than $10^{30}$cm$^{-2}$s$^{-1}$ and later during TOTEM operation at $\sim 10^{28}$cm$^{-2}$s$^{-1}$. During these times no special beam conditions other than those planned for LHC commissioning and TOTEM operation will be needed. LHCf would be removed from the TAN and replaced by three Cu bar absorbers when the luminosity exceeds $10^{30}$cm$^{-2}$s$^{-1}$. After operation during TOTEM running and before removal it is possible that LHCf may request a short run with the position of one detector lowered and with crossing angle in one beam set at 140µrad downward in order to extend the range of accessible transverse momentum by 40%.

When LHCf is installed it will provide a robust luminosity measurement by selecting events that produce the $\pi^0$ invariant mass. The integration time for 10% luminosity measurement is relatively long, 100s for $L > 10^{28}$cm$^{-2}$s$^{-1}$ owing to 1kHz data rate limitation. However the robustness of the signal should make it very useful for corroborating other luminosity measurements during early commissioning and operation of LHC.

The decrease in sensitivity of the BRAN when Cu bars are replaced by LHCf is estimated to be a factor of $\sim 5$ to 10. However the integration times required for 1% BRAN luminosity measurements are short enough (3.6 and $\sim 18$ to 36s respectively at $10^{29}$cm$^{-2}$s$^{-1}$) that there should be little impact on LHC Operations.

Removal of LHCf and re-installation after LHC has operated at high luminosity requires developing a strategy for removal and storage of activated Cu bars in the TAN.

### 5.6 Safety

#### 5.6.1 Radiation safety

LHCf Phase-1 run is operation during initial beam commissioning and low luminosity running of LHC with 43 bunches per beam. Because the radiation hardness of the LHCf detectors is not sufficient for luminosity greater than $10^{30}$cm$^{-2}$s$^{-1}$, the detectors are removed when the luminosity reaches this level.

Absorbed dose in this phase can be estimated by two ways. According to Ref [31], absorbed dose at center of neutral particles incident on the TAN, where the LHCf detector will be installed, is estimated to be $\sim 10^8$ Gy/year at maximum for 1 year operation with $10^{34}$cm$^{-2}$s$^{-1}$ luminosity. If we simply scale down absorbed dose to the case of $10^{30}$cm$^{-2}$s$^{-1}$
luminosity for LHCf case, the absorbed dose for LHCf detector will be \( \sim 10^4 \) Gy/year. Typically plastic scintillator and clear optical fibers do not start degradation until 10kGy exposure. Therefore this rough estimation gives an idea that the entire LHCf detector will survive with \( 10^{30} \text{cm}^{-2}\text{s}^{-1} \) luminosity for a “year” of operation corresponding to 180 days.

The front-end electronics boards for the SciFi are installed inside the upper part of the detector housing and will be at least 20cm from the center of the neutral particle flux. The absorbed dose at this position is expected to be 10Gy/yr from Ref [31] so assuming a typical tolerance of 100 Gy the front-end electronics should not suffer significant radiation damage. The ASICs for the Si strip detectors can withstand a much higher radiation dose, up to 140kGy without a significant degradation of performance.

The contact dose of the LHCf detectors after Phase-1 operation is also estimated from Ref [31]. It is conservatively expected to be less than \( 10^{-3} \) to \( 10^{-2} \) mSv/hr (30 day operation at \( 10^{30} \text{cm}^{-2}\text{s}^{-1} \), one day cool down) and therefore not require special remote handling procedures.

At the beginning of Phase-2 the activation of the Cu bars may exceed 0.1 mSv/hr contact dose and require remote handling for their removal and storage while LHCf is installed. At the end of Phase-2 and before return to high luminosity operation LHCf would be removed and replaced by three Cu bars.

5.6.2 Non-flammable issues

We use standard Halogen-free cables available at CERN for all the cables in the tunnel between LHCf detectors and USA15.
<table>
<thead>
<tr>
<th>Item</th>
<th>Detector #1</th>
<th>Detector #2</th>
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</thead>
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<td>Japan - Shibaura</td>
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<td>Mechanics</td>
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<td>Japan - Nagoya</td>
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<tr>
<td>Plastic Scintillators</td>
<td>Japan - Nagoya</td>
<td>Japan - Nagoya</td>
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<td>Scintillating fibers</td>
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<td>Japan - Nagoya</td>
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<td>photomultipliers for scintillators</td>
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<td>Japan - Waseda</td>
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<td>Manipulator</td>
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Table 17: Responsibility for each detector item.

6 Project planning

6.1 Organization

Table 16 shows LHCf organization. Y.Muraki is the Spokesperson for LHCf. M.Hauenauer is the contact person. T.Sako is the Technical Coordinator. During the experiment many post-graduate course students from Japan will join and cover the shifts in addition to the present researchers.

<table>
<thead>
<tr>
<th>Spokesperson</th>
<th>Yasushi Muraki</th>
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<tbody>
<tr>
<td>Contact Person</td>
<td>Maurice Hauenauer</td>
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<tr>
<td>Technical Coordinator</td>
<td>Takashi Sako</td>
</tr>
</tbody>
</table>

Table 16: LHCf organization

6.2 Responsibility for construction

Table 17 summarize responsibility for construction.

Nagoya University will take responsibility for construction of the plastic scintillators and related electronics, the detector housing and detector assembly for both Detectors #1 and #2.

Waseda University and Kanagawa University will take responsibility for construction of the SciFi layers and related electronics for Detector # 1.

The Italian National Institute of Nuclear Physics (INFN Firenze and Catania) will take responsibility for construction of the Si trackers and related electronics for Detector # 2.
6.3 Budget and construction schedule

The prototype detector was completed in Japan by the end of 2004 using a Grant-in-Aid from the Ministry of Science and Education of Japan. The test beam experiment was performed with CERN SPS beamline. We have confirmed the prototype detector shows good performance as we expected. Preliminary results are summarized in Appendix A. During this period, we have also tested the new read-out system for SciFi at the CERN SPS.

If the LHCC approves our proposal, the additional budget for improving the detector will be approved by the Ministry of Science and Education of Japan in the fiscal year 2006. The Italian collaborators will prepare Si layers and related electronics for Detector # 2. The fully completed Detector # 1, and a part of Detector # 2, including 1 or 2 layers of silicon sensors, will be assembled and shipped to CERN in middle of 2006 for exposure to a test beam in either the North or West Areas of CERN in the summer of 2006.

The remaining layers of silicon sensors will be prepared before the end of 2006, and Detector #2 will be fully assembled before the end of the year.

The LHCf experiment will then be installed in the tunnel some time between the end of 2006 and early 2007; the installation will proceed in 2 phases: first Detector #1 and later Detector # 2. The experiment will be ready for data taking by June of 2007.

The costs related to the installation topics and to the general infrastructures (cables and their pulling, power supply, computer etc.) will be shared between Japan institutes and INFN.

The summary of detector cost is shown in Table 18.
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<th>Detector #1</th>
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Table 18: Summary of LHCf detector cost (in kCHF). Only the cost for material are shown.

6.4 Request for beam conditions and other support

Typical beam parameters suitable for the LHCf operation are shown in Tab 1. LHCf is to be a parasitic operation during early Stage 1 commissioning of the LHC when the luminosity is less than $10^{30}\text{cm}^{-2}\text{s}^{-1}$ and later during TOTEM operation at $\sim10^{28}\text{cm}^{-2}\text{s}^{-1}$. During these times no special beam conditions other than those planned for LHC commissioning and TOTEM operation will be needed. LHCf would be removed from the TAN and replaced by three Cu bar absorbers when the luminosity exceeds $10^{30}\text{cm}^{-2}\text{s}^{-1}$. 

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After operation during TOTEM running and before removal it is possible that LHCf may request a short run with the position of one detector lowered and with crossing angle in one beam set at 140μrad downward in order to extend the range of accessible transverse momentum by 40%.

We would like to request the help of CERN support staff for further integration work of the LHCf detectors into the TAN absorbers and for installation of the detectors and associated cables and electronics. We have requested two weeks for testing LHCf detectors in an SPS beam in the summer of 2006 in order to calibrate absolute energy scale of the calorimeters.
7 Appendix A : Test beam experiments of prototype calorimeter

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. 59.
Figure 59: (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.

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. 60 shows the energy resolution of the 2x2 and 4x4 cm² shower counters for electrons with beam energy 50-250 GeV/c. Monte Carlo calculations can reproduce the experimen-
tal results very well.

Figure 60: 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. 61 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. 62 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. 63. 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. 64 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. 64, still give result with resolution of the shower center better than 200 microns.
Figure 61: 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.

Figure 62: Escape corrected plot of Fig. 61. 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.
Figure 63: Schematic view of the set-up of the test experiment.

Figure 64: 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.

Fig. 65 represents the lateral distributions of shower particles produced by 200 GeV electrons at 10 r.l.. The data were obtained with the 4x4cm$^2$ 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. 65, 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.

Figure 65: 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.

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. 66. The variation of light collection efficiency from the center to the corner of a calorimeter is about ±7%. The data in Fig. 66 can be used to correct for the position dependence of the light intensity collected from the plastic scintillators.
Figure 66: 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.
References

phi/0507150).
press.
http://www.ifcai.pa.cnr.it/EUSO/docs/EUSOproposal.pdf
[18] A. Rossi, “Residual Gas Density Estimations in the LHC Insertion Regions IR1 and
IR5 and the Experimental Regions of ATLAS and CMS for Different Beam Operations”,
Workshop Chamonix XIV, 17-21 Jan 2005;


[26] EPICS. See http://cosmos.n.kanagawa-u.ac.jp/.


