Chapter 1

Introduction

1.1 Physics of the LHCf experiment

Research on the highest energy cosmic-rays (energy above 10^{19} eV) has great scientific interest since their origin, propagation and interactions are unknown and may yield information about new physics. To give an idea of the type of information available we briefly summarize the situations with the spectrum and composition of the highest energy cosmic rays and then describe how the LHCf experiment can make a contribution to this field.

Ten years have passed since the air shower experiment AGASA reported that the cosmic ray spectrum at the highest energy may extend beyond 10^{20} eV and the GZK cut-off might not exist [1]. If this were true, the origin of the highest energy cosmic-rays would need an exotic explanation like the decay of cosmic strings or Z_0 bursts [2] and so on. However another result obtained by the HiRes experiment was consistent with the existence of the GZK cut-off [3]. The AGASA experiment used a large array of surface detectors whereas the HiRes experiment employed a novel calorimetric technique utilizing observation of atmospheric fluorescence. Recently new results have been published by the Auger collaboration at the international cosmic-ray conference ICRC07 [4]. Auger employs a combination of surface detectors and atmospheric fluorescence telescopes and the new results support the existence of the GZK cut-off. The results of these three experiments are shown in figure 1.1. If the energy scale of the AGASA results were reduced by 45% then their results would be in agreement with the others.

Measurement of the chemical composition of the highest energy cosmic rays can also give important information about where they are produced. Several astronomical candidates for the production of the highest energy cosmic rays have been discussed in the literature and the maximum energy obtained depends on the composition to be accelerated. The highest energy cosmic-rays can travel through nearby inter-galactic space almost without deviation by magnetic fields. Auger has reported that the arrival direction of the highest energy events is correlated with the distribution of active galactic nuclei (AGN) [5]. This naturally suggests that the primaries are most likely protons. However composition measurements reported by Auger indicate that the primary composition is a mixture of protons and heavy nuclei (Fe) up to the highest energy where they so far have sufficient statistics for composition analysis - 4×10^{19} eV [6].

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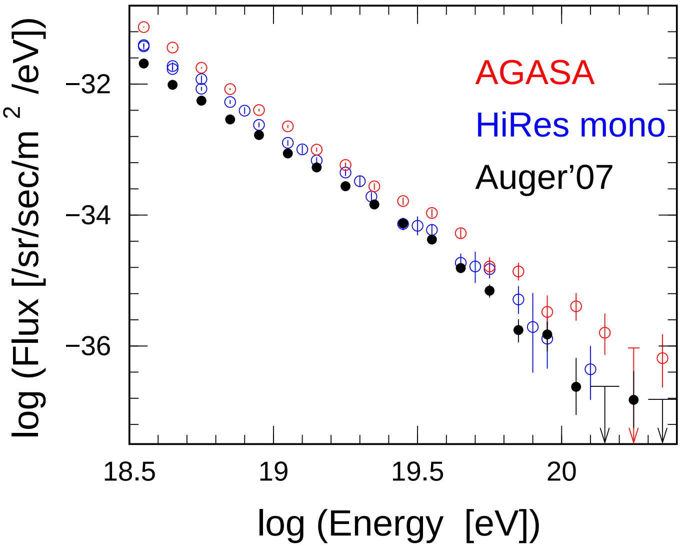

Figure 1.1: Energy spectra of primary cosmic-rays obtained by three large experiments. The red, blue and black points represent the result of AGASA, HiRes and Auger, respectively.

If it turns out that the highest energy primaries have significant Fe composition then the "GZK-cut off"-like feature could perhaps be interpreted as photo-dissociation by cosmic microwave background (CMB) photons. Further investigations are needed for a consistent understanding of all measurements.

It is well known that understanding the results of cosmic ray experiments depends strongly on the use of Monte Carlo codes. However the hadronic interaction models used in these codes have not been verified experimentally near the GZK energy region 10^{20} eV which is 6 orders of magnitude higher than the laboratory equivalent energy of the S$p\bar{p}$S or Tevatron. The perturbative QCD models used for simulation of air shower experiments are essentially phenomenological models calibrated with experimental data where they are available. So far only data from the UA7 experiment taken at the S$p\bar{p}$S have been available for calibration of the forward neutral pion production spectrum at 10^{14} eV [9]. The 14 TeV center of momentum energy of the Large Hadron Collider (LHC) will push the laboratory equivalent collision energy up to 10^{17} eV.

There are two key quantities at the primary interaction vertices which determine the development of air showers; the total inelastic cross section and the particle production energy spectra at very forward angles. The former will be measured at LHC with roman pot detectors such as employed by the TOTEM [7] or ATLAS collaborations [8]. Therefore a new measurement on forward production spectra in LHC is strongly desired to calibrate the models at 10^{17} eV. LHCf is an experiment to perform a measurement of the very forward production cross sections and energy spectra of neutral pions and neutrons. Measurement will be done in a short period during the early phase of the LHC commissioning before the luminosity reaches $10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In this paper, an overview of the LHCf instrumentation is given. Previous study of the prototype detectors is found elsewhere [10]. After providing an outline of the LHCf experiment in section 1.2, the details of the detectors and the data acquisition system will be described in section 2 and section 3, respectively. In section 4, simulation studies of the expected performance during the LHC operation and the first results from beam tests performed in 2007 at the CERN SPS are reported.

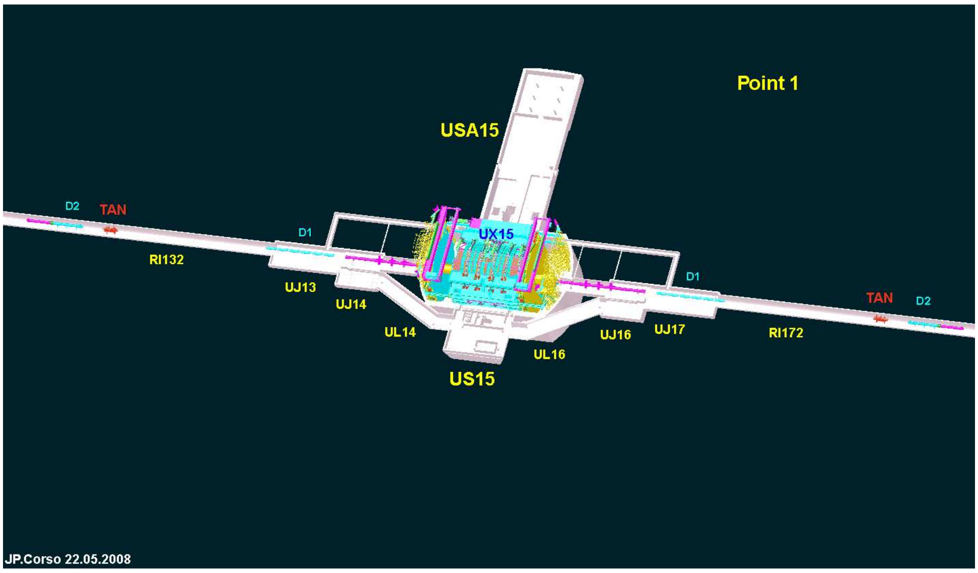

Figure 1.2: Geometry of the IP1 area of LHC. The structure seen in the center represents the ATLAS detector surrounding the interaction point. The straight line from top-left to bottom-right indicates the long straight section of the LHC tunnel and the LHCf detectors are installed at the places marked ’TAN’ at both sides of IP1.

1.2 Experimental overview

The LHC has massive zero degree neutral absorbers (Target Neutral Absorber; TAN) located $\pm$140 m from interaction points (IP) 1 and 5 in order to protect the outer superconducting beam separation dipoles (D2) from neutral particle debris from the IP (figure 1.2, figure 1.3). Charged particles from the IP are swept aside by the inner beam separation dipole D1 before reaching the TAN. Inside TAN the beam vacuum chamber makes a Y shaped transition from a single common beam tube facing the IP to two separate beam tubes joining to the arcs of LHC. The Y-chamber has been carefully machined to have a uniform one radiation length projected thickness over a 100 mm$\times$100 mm square centered on the zero degree crossing angle beamline. In the crotch of this “Y-chamber”, just behind the 100 mm$\times$100 mm square there is an instrumentation slot of 96 mm$^w\times$ 607 mm$^h\times$ 1000 mm^l extending from 67 mm below the beam height to the top of the TAN. The aperture for the LHCf measurements is limited by the width of the slot and by the vertical aperture of the beam pipe in the D1 dipole projected to the TAN. The cross sections of the D1 beam pipe projected to the detector plane and of the instrumentation slot of the TAN are drawn in figure 1.4. This unique location covers the pseudo-rapidity range from 8.4 to infinity.

The LHCf detectors are two independent shower calorimeters inserted in the TAN instrumentation slots on both sides of IP1. Each occupies a 300 mm length in the most upstream position of the instrumentation slots followed by BRAN luminosity monitors 100 mm in length [12] and finally the ATLAS ZDCs [11]. Both the LHCf detectors consist of a pair of small sampling and imaging calorimeters made of plastic scintillators interleaved with tungsten converters. Position sensitive layers are inserted in order to provide incident shower positions. The two detectors are similar, but use different techniques and geometry for the purposes of redundancy and consistency checks of

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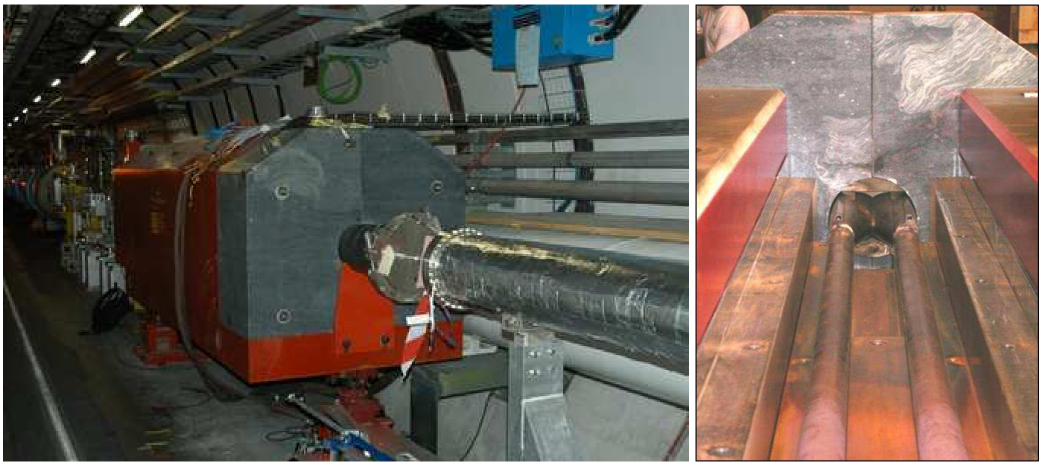

Figure 1.3: Photo of the TAN absorber located 140 m from the IP. Left: TAN fully assembled in the LHC tunnel seen from the IP side. Right: TAN during assembly at CERN seen from the top facing the IP. The 96 mm gap between the two beam pipes allows space for installation of detectors.

the measurements. In addition, coincidence between these detectors may be useful for rejection of background due to beam-gas interactions and for application to diffractive physics. The calorimeters are designed to have energy and position resolutions better than 5% and 0.2 mm, respectively. With such properties, the experiment will be able to discriminate between the major interaction models used in cosmic-ray studies, or to construct new models. In this paper, the detector installed in LSS1L (Arm 1; IP8 side) is referred as detector 1 and the detector installed in LSS1R (Arm 2; IP2 side) is referred as detector 2. Standing inside the LHC ring and looking at IP1, detector 1 is on the left and detector 2 is on the right.

Both detectors are supported by manipulators mounted to the top surface of the TAN in order to have the capability of remotely moving the detectors vertically by a 120 mm stroke. Figure 1.4 shows the geometrical configuration of each detector viewed from IP1. In default setting, the center of the smaller calorimeters is placed on the horizontal midplane. Using the manipulators to move the detectors vertically from their default positions increases the range of P_T that can be measured. The P_T range would be further increased by operation with a non-zero beam crossing angle of 140 μrad, because the center of neutral particle flux moves downward. The geometry of detector 2 is designed to maximize the P_T coverage without scanning and/or employing a finite crossing angle. In front of each detector, a Front Counter (FC) made of plastic scintillators is inserted. They provide useful trigger information by covering a larger aperture than the calorimeters.

With these detectors we will be able to identify γ-rays, measure the γ-ray energy spectrum (>100 GeV) with a few per cent energy resolution, measure the γ-ray incident position and reconstruct the γ-ray pair invariant mass distribution that shows a clear peak at the neutral pion mass. Hadron showers of high energy neutrons at zero degrees can be also measured, however, with decreased energy resolution of about 30%.

LHCf is not designed to be a radiation hard detector and so will be removed when the LHC luminosity exceeds 10^{30} cm^{-2}s^{-1}. Owing to the limitations imposed by radiation and the configuration of the DAQ, data taking of LHCf is planed for the 43 bunch operation and 10^{10} protons per

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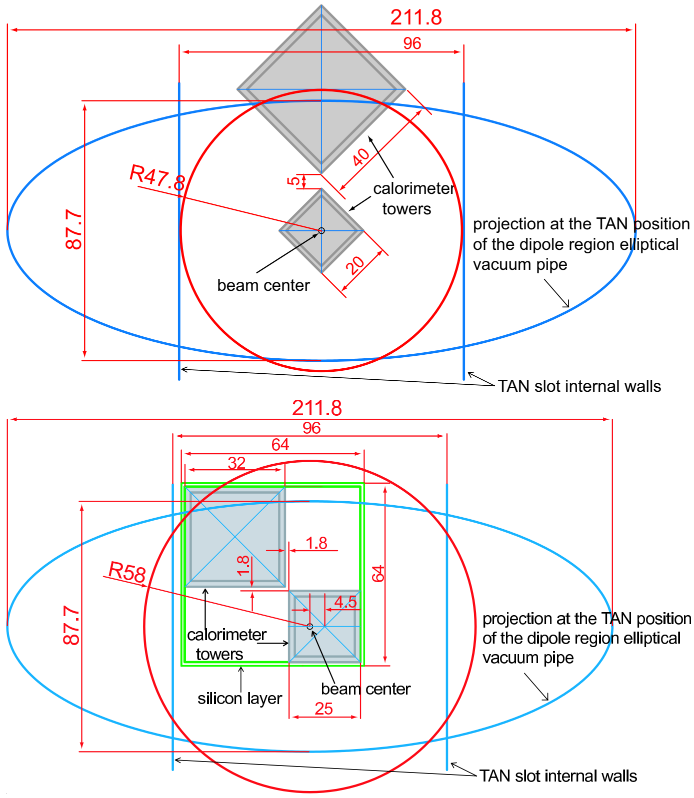

Figure 1.4: Cross sections of detector 1 (top) and detector 2 (bottom). Grey squares indicate the calorimeters in the detectors while a green square shows the coverage of the silicon strip sensor. Vertical and elliptical blue lines indicate the physical aperture limited by the walls of the TAN and the beam pipe, respectively.

bunch which are foreseen at the very beginning of LHC commissioning. At this low intensity and luminosity ($10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) a few minutes of data taking can provide enough statistics to discriminate between hadron interaction models. After a week or so of operation it is anticipated that the LHCf detector will be removed from TAN during a brief machine stop. In the absence of LHCf three Cu bars (each $94\,\mathrm{mm}^{w} \times 605\,\mathrm{mm}^{h} \times 99\,\mathrm{mm}^{l}$) will occupy the region in front of the BRAN. The purpose of the Cu bars is to generate showers for detection by the BRAN as well as to provide shielding for the downstream D2 magnets. The LHCf calorimeters and the Cu bars have nearly the same length in nuclear interaction lengths so the BRAN signals will be very similar for operation with LHCf and with the Cu bars.