LHCf: an accelerator experiment for Cosmic Ray Physics

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The LHCf Collaboration

Trieste, May 28, 2007 - QCD at Cosmic Energies

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LHCf
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Outline

- Introduction
  - Main problems in HECR physics: GZK cut off, chemical composition

- Idea of LHCf
  - Measurement of neutral particles emitted very forward at LHC

- Simulation and test beam results
  - Performances of the detector

- Conclusions, plans and schedule
  - Toward the LHC operation
Introduction: GZK cut off

AGASA reports 18% systematic uncertainty in energy determination.

10% of systematic is due to interaction model.

Accelerator calibration is necessary.

Different interaction model gives different answers for the primary cosmic ray energy estimate.

Huge experiment (Auger, TA) will solve the statistics.

$\text{GZK cutoff: } 10^{20}\,\text{eV}$

Huge experiment (Auger, TA) will solve the statistics.

$\text{20% correction on the absolute energy scale!!}$

$\text{29th ICRC, Pune (India)}$
Introduction: cosmic ray composition

Not only GZK...

Different interaction models lead to different conclusions about the composition of the primary cosmic rays.
Composition: inferred from $X_{\text{max}}$

Spectrum: Energy is measured by counting the secondaries

Simulation plays a crucial role

LHCf is a tool to calibrate the simulation
Development of atmospheric showers

- The dominant contribution to the energy flux is in the very forward region ($\theta \approx 0$).

- In this forward region the highest energy available measurements of $\pi^0$ cross section were done by UA7 ($E=10^{14} \text{ eV}, y=5-7$).

Simulation of an atmospheric shower due to a $10^{19} \text{ eV}$ proton.
Longitudinal development of showers

The direct measurement of the $\pi$ production cross section as function of $p_T$ is essential to correctly estimate the energy of the primary cosmic rays.

DPMJET, QGSJET, SIBYLL ... are normally used. Factor 2 of discrepancy.

Sea Level

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Summarizing...  
LHC-HECR interplay

Calibration of the models at high energy is mandatory

We will use LHC, the highest energy accelerator

7 TeV + 7 TeV protons  
14 TeV in the center of mass  

\[ E_{\text{lab}} = 10^{17} \text{ eV} \quad (E_{\text{lab}} = E_{\text{cm}}^2 / 2 m_p) \]

Major LHC detectors (ATLAS, CMS, LHCB) will measure the particles emitted in the central region

**LHCf will cover the very forward part**  
May be also heavy ions collisions????

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The LHC ring

LHC PROJECT

27 km ring

ATLAS

CMS

Point 1

Point 3.2

Point 3.3

Point 4

Point 5

Point 6

Point 7

Point 8

ATLAS

CMS

ALICE

SPS

IP1

LHC-b

UNDERGROUND WORKS

LHC Works under way
Existing structures
LHC Project structures
**LHCf: Location and Experimental Layout**

**Detector I**
- Tungsten
- Scintillator
- Scintillating fibers

**Detector II**
- Tungsten
- Scintillator
- Silicon mstrip

**INTERACTION POINT**
- IP1 (ATLAS)

**Beam line**

140 m

**Detectors should measure energy and position of γ from π⁰ decays**
- e.m. calorimeters with position sensitive layers

**Two independent detectors on both side of IP1**
- Redundancy
- Background rejection (especially beam-gas)

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Detectors will be installed in the TAN region, 140 m away from the Interaction Point, in front of luminosity monitors.

Here the beam pipe splits in 2 separate tubes.

Charged particle are swept away by magnets!!!
The TAN and LHCf
Detector #1

2 towers ~24 cm long stacked vertically with 5 mm gap
Lower: 2 cm x 2 cm area
Upper: 4 cm x 4 cm area

Absorber
22 tungsten layers 7 mm thick \(ightarrow\)
44 \(X_0\) (1.6 \(\lambda_i\)) in total
(W: \(X_0 = 3.5\) mm, \(R_M = 9\) mm)

Energy

4 pairs of scintillating fiber layers for tracking purpose (6, 10, 30, 42 r.l.)

Impact point (\(\eta\))

\[\theta < 300 \mu\text{rad}\]

16 scintillator layers (3 mm thick)
Trigger and energy profile measurements

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Transverse projection of detector #1 in the TAN slot
We use LHC style electronics and readout.

4 pairs of silicon microstrip layers (6, 12, 30, 42 r.l.) for tracking purpose (X and Y) \(\rightarrow\) impact point.

16 scintillator layers (3 mm thick)

Trigger and energy profile measurements

Energy

Absorber
22 tungsten layers 7mm thick

\(\rightarrow\) 44 \(X_0\) (1.6 \(\lambda_i\)) in total
(W: \(X_0 = 3.5\) mm, \(R_M = 9\) mm)

2 towers 24 cm long stacked on their edges and offset from one another

Lower: 2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm

\(\theta < 400\) \(\mu\)rad
Transverse projection of detector #2 in the TAN slot

Maximization of the acceptance in R (distance from beam center)
Arm 1

Arm 1 was fully assembled in Japan in July 2006 (scintillators + fibers + Tungsten) and fully tested at CERN in August 2006 beam test.
Scintillating fibers readout (Arm1)

Hamamatsu
64 ch (8x8)
8 dynode

MAPMT

VA32HDR14 chip from IDEAS
• 1 $\mu$s shaping time
• Huge dynamic range (30 pC)
• 32 channels

MAPMT+FEC

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**Arm 2**

- Arm2 was partially assembled in Florence in July 2006 and brought to CERN for the Beam Test of August 2006
- Arm2 was fully assembled in Florence in April 2007
Silicon \(\mu\)strips readout

Pace3 chips
(many thanks to CMS preshower!!!)

- 32 channels
- 25 ns peaking time
- High dynamic range (> 400 MIP)
- 192x32 analog pipeline
The mechanics of the module

- Light Guides + Scintillators
- Hybrid circuit
- Pace Chips
- Kapton fanout
- Silicon sensor
- Tungsten
- SiliconX
- SiliconY
- 25 mm
Front Counter (Both for Arm1&2)

read by a MAPMT
R7600U-00-M4

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Now the real installation in LHC...

The idea is that installation takes place in 2 steps:
- Pre-installation
- Final installation

In between the 2 installation the baking out of the beam pipe will be done (200 °C), so the detectors should be removed

Pre-Installation dates have been fixed in Fall 2006
- LSS1L (Arm1)
  - 8/01/2007 to 26/01/2007 → FINISHED!
- LSS1R (Arm2)
  - 23/04/2007 to 11/05/2007 → FINISHED

The dates for the final installation are still under discussion
Arm1 pre-installation

From 8/01/2007 to 26/01/2007

No major problems came out

Cables → OK
Transport and installation → OK
Laser calibration → OK
Power supply from USA15 → OK
Manipulator and movements → OK

Arm1 was dismounted at the end
Transport and insertion in the TAN

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LHCf Arm 1 – Installation completed within 15 minutes!
Arm2 pre-installation

From 23/04/2007 to 11/05/2007

No major problems came out

Cables → OK
Transport and installation → OK
Laser calibration → OK locally

remote
Power supply from USA15 → OK
Manipulator and movements → OK

No interference with BRAN

Arm2 was dismounted on May 9
LHCf Physics performance

1. Single photon spectrum
2. $\pi^0$ fully reconstructed (1 $\gamma$ in each tower)

$\pi^0$ reconstruction is an important tool for energy calibration ($\pi^0$ mass constraint)

Basic detector requirements:
- minimum 2 towers ($\pi^0$ reconstruction)
- Smallest tower on the beam (multiple hits)
- Dimension of the tower $\rightarrow$ Moliere radius
- Maximum acceptance (given the LHC constraints)
Examples of simulated events for $\gamma$ and $n$
A vertical beam crossing angle $> 0$ will increase the acceptance of LHCf.
LHCf performances: single $\gamma$ geometrical acceptance

Some runs with LHCf vertically shifted few cm will allow to cover the whole kinematical range.
LHCf performances: $\gamma$ shower in Arm #2

500 GeV $\gamma$ shower

Fluka based simulation

Position resolution of detector

7 $\mu$m for 1.8 TeV $\gamma$

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LHCf performances: $\pi^0$ mass resolution

- Fitting Function: gauss + a*x + b
- Fitting parameters of gauss:
  - mean = 134.8 MeV
  - sigma = 7.1 MeV

Arm #1
- $\Delta E/E = 5\%$
- 200 $\mu$m spatial resolution

$\Delta m/m = 5\%$
**LHCf performances: Monte Carlo γ-ray energy spectrum (5% Energy resolution is taken into account)**

10^6 generated LHC interactions → 1 Minute exposure@10^{29} cm^{-2}s^{-1} luminosity

Discrimination between various models is feasible

Quantitative discrimination with the help of a properly defined χ^2 discriminating variable based on the spectrum shape (see TDR for details)
\( \gamma \) ray energy spectrum for different positions

Gamma Energy Spectrum of 20mm calorimeter at Center

- QGSJETII
- SIBYLL

 gamma energy spectrum for different positions

Gamma Energy Spectrum of 20mm calorimeter at 30mm shift

- QGSJETII
- SIBYLL

\( \chi^2/\text{DOF} = 107/125 \) for QGSJET
\( \chi^2/\text{DOF} = 224/125 \) for DPMJET3
\( \chi^2/\text{DOF} = 816/125 \) for SYBILL

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LHCf performances: $\pi^0$ geometrical acceptance

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LHCf performances: energy spectrum of $\pi^0$

Typical energy resolution of $\gamma$ is 3% at 1TeV
LHCf performances:
model dependence of neutron energy
distribution

Original n energy

30% energy resolution

Neutron Energy Distributions

Counts / [100GeV/10^14\text{m}]

QGSJET
QGSJET II
DPMJET3
SIBYLL

Neutron Energy Spectrum
of 20mm Calorimeter at beam center

particle/bin

DPMJET3
QGSJET
QGSJETII
SIBYLL
30% Energy Resolution

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Estimate of the background

- beam-beam pipe
  - \( E_\gamma(\text{signal}) > 100 \text{ GeV}, \text{ OK} \)
  - background < 1%

- beam-gas
  - It depends on the beam condition
  - background < 1% (under \( 10^{-10} \text{ Torr} \))

- beam halo-beam pipe
  - It has been newly estimated from the beam loss rate
  - Background < 10% (conservative value)
The LPM effect
Landau – Pomeranchuk - Migdal

Increase of $X_0$ with increasing $\gamma$ energy

LHCf is able to directly measure the LPM effect!

- CERN : SPS T2 H4
- Incident Particles
  - Proton 150,350 GeV/c
  - Electron 100,200 GeV/c
  - Muon 150 GeV/c

Tests were successful

- Energy resolution
- Energy calibration
- Spatial resolution of the tracking systems

Setup

- LHCf Detector
- Silicon Tracker
- Moving Table
- Trigger Scintillator
An electron event as seen by Arm1

40mm Calorimeter : 196 GeV electron

Transition Curve

Scifi

2 r.l. step  4 r.l. step

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Leakage Correction

MC predicts that the leakage is energy independent!

Prototype Experiment

Monte Carlo

Distance from Edge

MC Leak Normalised

MC Leak Normalised to 200GeV/c

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Performances of the LHCf Detector

Measured at the SPS

Beam Test in 2004

SciFi Position Resolution

Energy Resolution

LHCf can measure (and provide to LHC) the center of neutral flux from the collisions

If the center of the neutral flux hits LHCf

$\Rightarrow \ll 1 \text{ mm resolution}$

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Energy Calibration

Problem: Determination of the conversion factor from ADC to Energy in each calorimeter layer
⇒ \( A_i \) [ADC counts/MeV] (i: Layer)

**How to do?**
Compare data with simulation (EPICS), tuning with beam test data

**Event Selection (Centered events)**
Incident point
- 20mm \( \rightarrow \) 3mm from calorimeter center
- 40mm \( \rightarrow \) 5mm from calorimeter center

Beam Profile
40mm Calorimeter
196 GeV e\(^-\) RUN
Data vs. Simulation

40mm Calorimeter: 196 GeV

Red: Simulation  Black: Experiment

\[ Ai = \frac{\text{Mean(data)}}{\text{Mean(simulation)}} \]

<table>
<thead>
<tr>
<th>Layer</th>
<th>( \chi^2 )</th>
<th>D.O.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>42.6</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>23.8</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>50.0</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>64.5</td>
<td>38</td>
</tr>
</tbody>
</table>

Simulations and data agrees well!!!

Energy scale can be well inferred

Work in progress to check the energy scale for different energies

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Few plots of the beam test results for silicon

A high energy electron shower seen on $x$ and $y$ silicon

<Noise> ~ 5 ADC counts
Energy measured
100 GeV electrons
High Gain
The LHCf operation in LHC
## Optimal LHCf run conditions

<table>
<thead>
<tr>
<th>Beam parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td># of bunches</td>
<td>$\leq 43$</td>
</tr>
<tr>
<td>Bunch separation</td>
<td>$&gt; 2 \mu\text{sec}$</td>
</tr>
<tr>
<td>Crossing angle</td>
<td>0 rad</td>
</tr>
<tr>
<td></td>
<td>140 $\mu\text{rad}$ downward</td>
</tr>
<tr>
<td>Luminosity per bunch</td>
<td>$&lt; 2 \times 10^{28} \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\leq \sim 10^{30} \text{cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$4 \times 10^{10}$ ppb ($\beta^* = 18 \text{ m}$)</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{10}$ ppb ($\beta^* = 1 \text{ m}$)</td>
</tr>
</tbody>
</table>

Beam parameters used for commissioning are good for LHCf!!!

No radiation problem for 10kGy by a “year” operation with this luminosity.
Trieste, May 28, 2007

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**Parameter evolution and rates**

\[ L = \frac{N^2 k_b f y}{4 \pi \varepsilon_n \beta} \]

**Event rate / Cross-section**

\[ \text{Event rate / Cross-section} = \frac{L \sigma_{\text{tot}}}{k_b f} \]

---

**Optimal conditions for LHCf running!**

---

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 (and 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_b )</td>
<td>( N )</td>
<td>( \beta )</td>
<td>( l_{\text{beam}} )</td>
</tr>
<tr>
<td>43</td>
<td>4 ( 10^{10} )</td>
<td>11</td>
<td>1.7 ( 10^{12} )</td>
</tr>
<tr>
<td>43</td>
<td>4 ( 10^{10} )</td>
<td>2</td>
<td>1.7 ( 10^{12} )</td>
</tr>
<tr>
<td>156</td>
<td>4 ( 10^{10} )</td>
<td>2</td>
<td>6.2 ( 10^{12} )</td>
</tr>
<tr>
<td>156</td>
<td>9 ( 10^{10} )</td>
<td>2</td>
<td>1.4 ( 10^{13} )</td>
</tr>
<tr>
<td>936</td>
<td>4 ( 10^{10} )</td>
<td>11</td>
<td>3.7 ( 10^{13} )</td>
</tr>
<tr>
<td>936</td>
<td>4 ( 10^{10} )</td>
<td>2</td>
<td>3.7 ( 10^{13} )</td>
</tr>
<tr>
<td>936</td>
<td>6 ( 10^{10} )</td>
<td>2</td>
<td>5.6 ( 10^{13} )</td>
</tr>
<tr>
<td>936</td>
<td>9 ( 10^{10} )</td>
<td>1</td>
<td>8.4 ( 10^{13} )</td>
</tr>
<tr>
<td>2808</td>
<td>4 ( 10^{10} )</td>
<td>11</td>
<td>1.1 ( 10^{14} )</td>
</tr>
<tr>
<td>2808</td>
<td>4 ( 10^{10} )</td>
<td>2</td>
<td>1.1 ( 10^{14} )</td>
</tr>
<tr>
<td>2808</td>
<td>5 ( 10^{10} )</td>
<td>1</td>
<td>1.4 ( 10^{14} )</td>
</tr>
<tr>
<td>2808</td>
<td>5 ( 10^{10} )</td>
<td>0.55</td>
<td>1.4 ( 10^{14} )</td>
</tr>
</tbody>
</table>

R. Bailey, January 2007
LHCf proposed running scenario

✓ Phase-I
  ✓ Run since the very beginning of LHC operations (Stage 1, 43 bunches)
  ✓ Remove the detector for radiation issues when the machine goes to the Stage II (luminosity reaches $10^{31}$ cm$^{-2}$s$^{-1}$) and reinstall the 3 Cu bars

✓ Phase-II
  ✓ Re-install the detector at the next opportunity of low luminosity run after removal of Cu bars (Totem dedicated runs? Possible LHCf dedicated runs?)

✓ Phase-III
  ✓ Future extension for p-A, A-A run with upgraded detectors?
LHCf: conclusions and plans

- LHCf approved in June 2006 by the LHCC

- **Physics performances:**
  - able to measure $\pi^0$ mass with 5% resolution.
  - able to distinguish the models by measurements of $\pi^0$ and $\gamma$
  - able to distinguish the models by measurements of $n$

- **Detectors:**
  - Arm1 & Arm2 are fully ready
  - Test beams were done in 2004 & 2006 to measure the performances

- **Installation phase well advanced**
  - ARM1 already successfully pre-installed in January 07,
  - ARM2 already successfully pre-installed in April-May 07
  - Final installation dates are under discussion

- **Running conditions:**
  - Three foreseen phases
  - Phase I: Run at the beginning of LHC operations (43 bunches)
  - Phase II: operation during low luminosity TOTEM runs or dedicated runs
  - Phase III: Heavy ion runs?
Back up Slides
Epics v.s. Geant4

W: 7mm
Scintillator: 3mm x 16
100mm

Transition Curve

EPICS
GEANT4

\( \langle dE \rangle [\text{GeV}] \)

\( \frac{dE_{100\text{GeV}}}{dE_{200\text{GeV}}} \)

EPICS\( \frac{dE_{100\text{GeV}}}{dE_{200\text{GeV}}} \)/GEANT4\( \frac{dE_{100\text{GeV}}}{dE_{200\text{GeV}}} \)

RATIO

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Beam profile
200 GeV electrons
Table 3: Event rate of single $\gamma$'s and hadrons per inelastic collision for the Detector #1. Here the 2cm x 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 x 2cm tower is at the center of the neutral particle flux and with beam crossing angle of 140$\mu$rad.

<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>0.0949</td>
<td>0.0721</td>
</tr>
<tr>
<td>2. One Gamma Incident</td>
<td>0.0654</td>
<td>0.0528</td>
</tr>
<tr>
<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>

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.
\( \pi^0 \) rate

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

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. One Particle Incident on each Calorimeter</td>
<td>0.0040</td>
</tr>
<tr>
<td>2. Gamma Incident on each Calorimeter</td>
<td>0.0052</td>
</tr>
<tr>
<td>3. Invariant mass cut (125 MeV &lt; M_{\pi^0} &lt; 145MeV)</td>
<td>0.0007</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. One Particle Incident on each Calorimeter</td>
<td>0.0066</td>
</tr>
<tr>
<td>2. Gamma Incident on each Calorimeter</td>
<td>0.0052</td>
</tr>
<tr>
<td>3. Invariant mass cut (125 MeV &lt; M_{\pi^0} &lt; 145MeV)</td>
<td>0.0011</td>
</tr>
</tbody>
</table>

Table 8: Event rate of \( \pi^0 \) production per inelastic collision for Detector #2. Here the 2.5cm\( \times \)2.5cm calorimeter is at the center of neutral particle flux and the beam crossing angle is 0\( \mu \)rad.

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. One Particle Incident on each Calorimeter</td>
<td>0.0080</td>
</tr>
<tr>
<td>2. Gamma Incident on each Calorimeter</td>
<td>0.0063</td>
</tr>
<tr>
<td>3. Invariant mass cut (125 MeV &lt; M_{\pi^0} &lt; 145MeV)</td>
<td>0.0015</td>
</tr>
</tbody>
</table>
Effect of LHCf on BRAN measurement

LUMI monitor (BRAN) inside TAN is beyond LHCf (replacing 4th copper bar)

The effect of LHCf on BRAN measurements has been studied in the last months by simulation:

- Reduction of shower particles at BRAN
- Position dependence on beam displacement
  (question from machine peoples: if we shift by 1 mm the real beam, does the center of the measured neutral energy shifts by 1 mm?)
BRAN response vs beam position

Relative change of the reduction factors for BRAN with respect to the nominal value (center of the beam: nominal one)

If the position of beam center stays within a few mm from the beam-pipe center, the reduction factors do not change more than 10%

Arm #1

Arm #2

H. Menjo