The ATLAS Zero Degree Calorimeter

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1. Introduction

Zero Degree Calorimeters (ZDCs) will be installed on either side (at 140m downstream) of IP1. The ZDCs became an indispensable part of the RHIC program. Originally justified by heavy ion physics considerations they also played a significant role in the RHIC pp program and were also used for accelerator tuning in both the pp and heavy ion programs.

Since the 2003 RHIC run, PHENIX has implemented enhancements of our original ZDC design, which added both a position sensitive detector at hadronic shower maximum and a proton calorimeter. These have also played a significant role in PHENIX pp as well as Heavy ion physics and found application in accelerator diagnostics as described below.

The ATLAS ZDC design is basically complete but we are treating the Shower Maximum capability that we added to PHENIX as a separate R&D project and plan to reach a decision on this feature at the design review (6/06). The shower maximum could be realized by adding a separate layer at shower maximum (as we did in PHENIX) or at least partially by grouping fibers in the 1st 2 modules.

1.1. Role of Zero Degree Calorimeter in ATLAS

The primary role of the ZDC is in event characterization. The ZDC measures the participant number by sampling the spectator neutrons. This is equivalent to measuring the magnitude of the impact parameter. Since PHENIX has shown, using the ZDC shower maximum detector installed since Run III, that forward neutrons exhibit a strong directed flow, v_1, the ZDC can also measure the orientation of the impact parameter. There are several advantages to studying jet modification with respect to the reaction plane with the ZDC measurement as compared to a detector like the PHENIX Beam Beam Counters

- the ZDC is well separated from the central detector so this minimizes interference between jet structure and flow
- the v_1 signal is strongest in the ZDC region (see fig.3).

The secondary role of the ZDC is as a device for luminosity measurement. The ZDC (coincidence) cross-section can be reliably calculated[1]. The ZDC rate gives directly the absolute luminosity for Pb-Pb collider mode with an accuracy of better than 5%.

At RHIC the ZDC was used as a minimum bias trigger and the motivation for this trigger will be more significant at LHC. A prerequisite for measuring modification of jets in heavy ion collisions is the availability of baseline data. The baseline relevant for ATLAS heavy ion runs would consist of pp data taken at $\sqrt{s_{NN}}$=5.5 TeV or p-Pb collisions at the same energy. Alternately by analyzing heavy ion data according to centrality one can express modification in terms of the ratio -R_{CP}- the ratio of central to peripheral cross sections corrected for the number of binary collisions. Because the ZDC is efficient at all centralities, ZDC trigger data are the best source for peripheral data with well-understood number of binary collisions. The lower energy reference data, though desirable, may not be available until several years after the first heavy ion measurements.

Finally, the ZDC is needed to tag hard photoproduction events- particularly diffractive events in which there is otherwise only soft back to back jets to trigger on in the central detector. PHENIX experience in measuring Ultraperipheral J/psi photo-production shows that it is very useful if one or more neutron tags is present. A recent paper [2] calculates the fraction of hard photoproduction events where additional photon exchanges lead to nuclear breakup. We have incorporated the tagging fraction calculation of Baur et al. in our rate calculations [3]. This result is confirmed by the PHENIX J/psi measurement and the PHENIX measurement showed that it is essential for designing a low rate trigger [4].

2. Historical Connection

ATLAS people working on the ZDC were responsible throughout the development of the RHIC ZDCs and were recently responsible for the introduction of the ZDC shower maximum detector in the RHIC program and for design of a ZDC suitable for the LHC and simulation of its performance. The ATLAS simulation results are often shown by CMS as a generic proof of principle. Some of the highlights of the RHIC development are

1. calculation of the inclusive cross section for producing one or more neutrons in each ZDC at RHIC and LHC energies. This is frequently used as a minimum bias interaction trigger but since the cross section is calculated to $\leq 5\%$ it can also be used for luminosity normalization [1]

2. design of the RHIC tungsten ZDC by Denisov and White which we tested together with a copper absorber design by Strobele in a CERN testbeam [5]

3. experiment to evaluate centrality resolution with the ZDC in NA49 by Strobele, Gorodetzky and White [6]

4. analysis of ZDC cross sections with PHENIX data [7]

5. analysis of d-Au diffractive cross sections in PHENIX using the ZDC, ZDC shower maximum detector and the PHENIX fCal [8]

6. first measurment of J/psi ultraperipheral production at RHIC [4] and finally calculations of inclusive and diffractive hard photoproduction at the LHC [3]

We have also made several presentations to ATLAS and other LHC collaborations about the possible role of the ZDC in accelerator commissioning and LHC absolute luminosity determination and completed a CERN report on this topic [16].

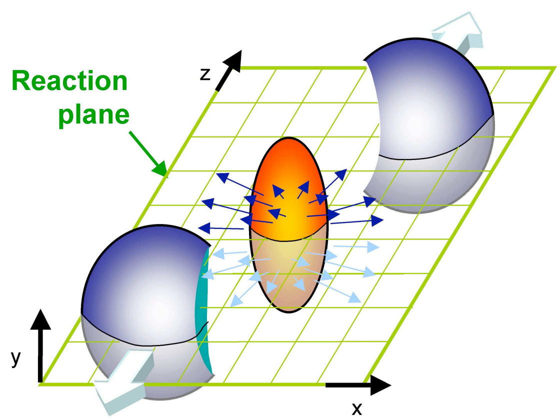

Figure 1. Collision geometry in heavy ion collisions. Both magnitude and direction of the impact parameter are measured by forward “spectator” remnants.

3. ZDC Project and Design issues

The ATLAS ZDC design differs from the RHIC design in that

- ATLAS configures the sampling fibers at 90^o to the beam direction (rather than 45^o)
- ATLAS uses hard clad silica core optical fibers (rather than PMMA fiber)

3.1. optics

The 90^o design was chosen for ease of integration with the Berkeley LHC ion chamber which will be installed together with the ATLAS ZDC

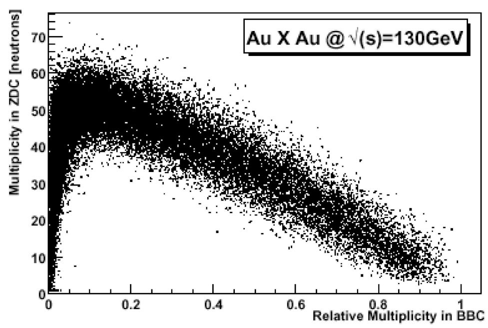

Figure 2. The ZDC measured neutron multiplicity (vertical scale) plotted against the "normalized" charged particle multiplicity in the BBC. These measurements sample the spectator number and participant number respectively and are combined to form an event centrality in PHENIX.

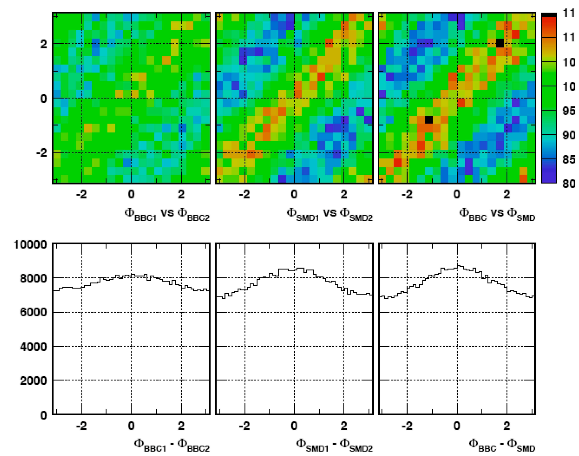

Figure 3. Correlation of reaction plane measurements in 2 forward hemispheres using BBC, ZDC shower maximum hodoscope and their combination.

and used by the accelerator controls group for beam commissioning. One consequence of the 90^o orientation is a reduction in light yield relative to 45^o since the Cerenkov light produced in the fibers is most easily captured at 45^o. The cost in light yield is approximately a factor of 3 but at LHC energy there is plenty of light. The choice of silica core fiber is the only option with acceptable radiation resistance and is completely based on the experience of NA50 at integrated doses of up 6Grad which should correspond to several years of LHC running. NA50 used NA=0.22 silica core-silica clad optical fiber from Spectran and showed that hard clad fiber suffered significant degradation of the cladding material at these doses, transmission of the fiber remains good but mechanical properties of the fiber deteriorate and hence the fibers should not be exposed to mechanical stresses.

3.2. ZDC PMT and light flasher

We have chosen a fine mesh 2 in. PMT from Hamamatsu (R5924) to read out each module. We make this choice to optimize signal speed and dynamic range (which was a performance issue at RHIC). The light flashers will use a laser light emitting diode (led) with good pulse amplitude stability and approximately the pulse shape of the ZDC shower signal. The purpose of the pulser system is to exercise the readout electronics chain and to do short term monitoring of PMT gain. The device should be stable to a few percent for temperature excursions of $\pm 5^0$ C.

4. LHC simulations

We have simulated the ZDC response to 2.75 TeV neutrons using GEANT3 simulation with identical treatment of production and capture of Cerenkov light in the optical fibres that we have used for RHIC ZDC simulations. The photomultiplier quantum efficiency is simulated using the Cerenkov light spectrum convoluted with the spectral response of the PMT(taken from the Hamamatsu data sheet). The ZDC configuration we simulated assumes that the first ZDC module will be followed by the ion chamber (treated here as 8 cm of inert copper) and then by either 2 or 4 identical ZDC modules. The simulation shows that 3 modules will yield an energy resolution of $\sigma_E/E = 24\%$ whereas with a total of 5 modules we achieve a resolution of 18%. We consider the 24% figure adequate for our physics program. It should also be noted that the large light yield (1500 photoelectrons) will ensure good ($\leq$ 100 psec) timing performance.

5. Beyond the ZDC

It is our plan to continue to study, at least through the period of prototype testing and fabrication, options which would enhance position resolution and EM shower measurements. In addition to the RHIC measurements with the shower maximum detector, other motivation for these developments comes from the approach of the LHCf collaboration. We are in contact with LHCf and are discussing collaboration beyond their initial measurements (which are scheduled for a 2 week dedicated run) towards a permanent enhancement of ATLAS forward energy flow measurements.

6. The case for the ZDC based on RHIC experience.

6.1. Physics case for the ZDC

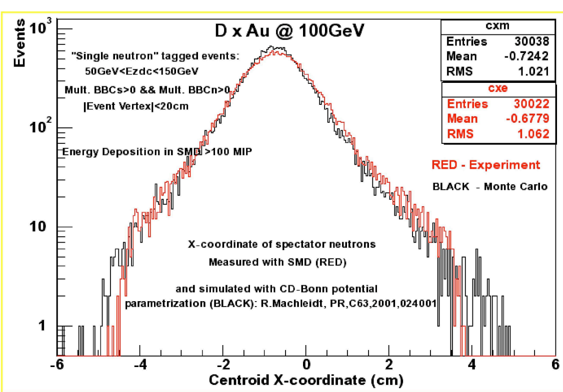

Figure 4. Distribution of forward neutrons and hence their p_T measured with the ZDC shower maximum hodoscope in d+Au dissociation events.

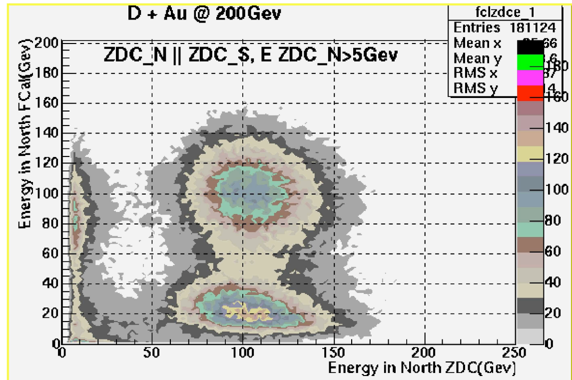

Figure 5. Energy distribution in the forward proton calorimeter vs. the ZDC showing the clear signal from $d + Au \rightarrow n + p + Au$.

The ZDC is a natural event characterization tool for Heavy Ion physics. In fixed target experiments the ZDC calorimeter intercepts all non-interacting (spectator) fragments of the incident nucleus so the number of participant nucleons is calculated exactly. This is equivalent to measuring the impact parameter of the collision. In a collider geometry the ZDC intercepts the neutral beam after an accelerator dipole so only the free neutron fraction of the spectators is sampled. A dedicated measurement [6] with the NA49 fixed target apparatus was carried out before the start of RHIC to compare event characterization with "neutrons only" vs. the full spectator measurement. These measurements showed that

1. a collider measurement (neutron only) gives a useful centrality determination so long as there is additional centrality information (ie central particle multiplicity) to resolve the ambiguity between central collisions (where there are only a few corona spectator neutrons) and peripheral collisions (in which many neutrons remain bound in larger nuclear fragments).

2. free neutrons are produced at essentially all centralities. There is negligible probability for the neutron spectators to fluctuate to

zero. This makes the ZDC coincidence an ideal min-bias trigger. It also allows one to calculate luminosity directly from the ZDC rate since the ZDC cross section corresponds to a calculable physics process and its acceptance is 100%.

Because the physics of beam fragmentation depends very weakly on center-of-mass energy it is not surprising that the NA49 observations have been shown to be valid at RHIC and must also hold at LHC. Here we list the ZDC physics role at RHIC also anticipated for ATLAS:

- Event Characterization: Figure 2 shows the ZDC total energy vs. the number of tracks in a hodoscope (BBC) covering $3 < |\eta| < 3.9$ in both + and - z direction in the PHENIX experiment from an unbiased set of Au-Au collisions in PHENIX. The centrality increases (impact parameter decreases) when moving from left to right in this plot. PHENIX analyzes centrality of collisions by dividing the band in Figure 1 into bins whose impact parameter or participant number can be calculated from the frequency of events in each bin. Using this so-called "clock method PHENIX obtains event centralities with a typical resolution of $3-5\%$.

- Reaction Plane: The first term in the Fourier expansion(v_1) of the azimuthal distribution of particles in a Heavy Ion event is called "directed flow". It is found to increase linearly with rapidity reaching a maximum in the beam fragmentation region covered by the ZDC and its shower maximum detector. The orientation of the flow and hence the reaction plane is observed via a displacement in the center of gravity of the ZDC energy deposition. Since, in Au-Au collisions, either beam direction provides an equivalent measurement of reaction plane, the combined resolution can be derived from the correlation between measurements in each beam. This is illustrated in Fig. 3 which shows the correlation in the Shower maximum compared with the Beam Beam counters. Not only is the reaction plane resolution better in the SMD but, being more forward, it is less sensitive to residual "non-flow" from jets measured in the central detector.

6.2. Performance in PHENIX d-Au run

The ZDC/SMD was used extensively in analyzing d-Au collision data taken by PHENIX during 2003. An analysis of the calculable d-Au dissociation (ie d+Au→ n+p+Au) reaction was used for luminosity normalization of the d-Au data set[8]. Fig. 4 shows the measured impact distribution compared to the calculated one derived from the expected neutron p_T distribution. The horizontal offset is an artifact of the eccentric orbit used in d-Au runs.

Fig. 5 shows a correlation plot of (neutron) ZDC energy vs. (proton) fCal energy along the deuteron beam direction (with 100 GeV/n beam energy) for an event sample with at least 5 GeV of energy deposit in the ZDC. An interesting feature of d-Au collisions is the stripping process in which only one nucleon in the deuteron interacts with the target. These events have 100 GeV deposit in either ZDC or fCal. Also seen in Fig. 5 is a clear dissociation signal- events with 100 GeV in both calorimeters. This process, first predicted by Glauber in his original analysis of diffraction dissociation, is used in PHENIX to obtain absolute luminosity calibration.

6.3. Performance for Accelerator commissioning

Figure 6 shows the coincidence rates of the ZDC and BBC in PHENIX during a Van der-Meer scan of a 100 GeV pp store. The counting rate due to beam-beam collisions is expected to have a gaussian dependence on the relative beam displacement during the scan in contrast to that of background processes such as beam-gas. Note that the ZDC rate is essentially Gaussian down to 10^{-4} of the peak rate. The background fraction is larger in the BBC graph as well as that of another hodoscope -the NTC. We found that we can measure the beam position in the SMD with sufficient accuracy to check the accelerator calculation of beam displacement during Van derMeer scans. Fig. 7 shows the correlation between measured horizontal position in the SMD (red points) and vertical position (black points) and the Van derMeer steps during a horizontal scan with step size of 0.2 mm.

7. ATLAS ZDC design

Fig. 8 shows an exploded view of one ATLAS ZDC module showing tungsten absorber and steel structural parts. The design allows easy replacement of the fiber ribbons, which will be installed between plates. Fig. 9 shows the installation of the ZDC in the TAN absorber at 140 m from IP1. Also shown is the ion chamber installed between modules 1 and 2. Only 3 of 4 modules will be installed in the current design but clearly the TAN slot has plenty of additional space along the beam direction.

8. Simulation Results

Fig. 10 Shows the results of Geant3 simulation of the ZDC response to neutrons with the nominal beam energy to be used for Pb-Pb runs in the LHC.

9. Acknowledgements

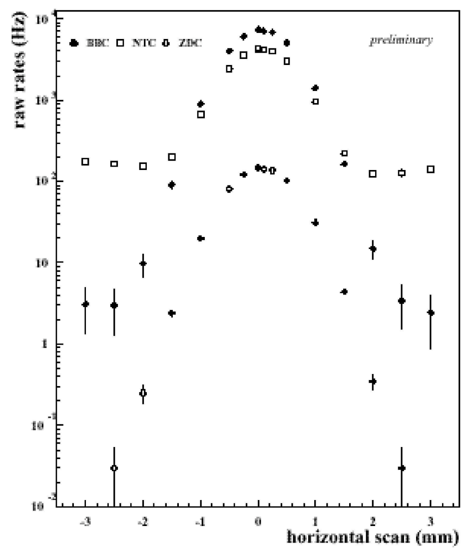

Figure 6. Vernier scan rates versus beam displacement in 3 different detectors. The ZDC rates are roughly 2 orders of magnitude lower than the BBC rate but apparently background free over several orders of magnitude.

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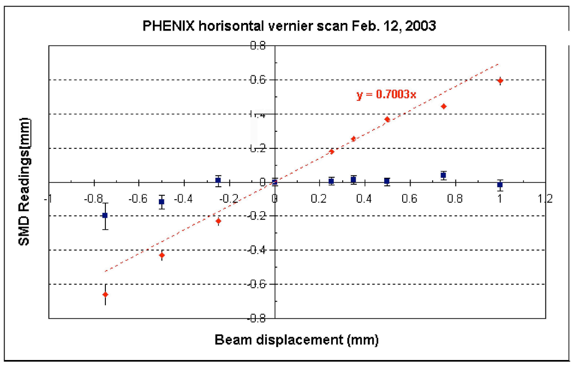

Figure 7. Horizontal Vernier scan displacement versus apparent beam displacement measured by the ZDC shower maximum hodoscope in d+Au collisions. Also shown for comparison is the vertical sower measurement (closed squares).

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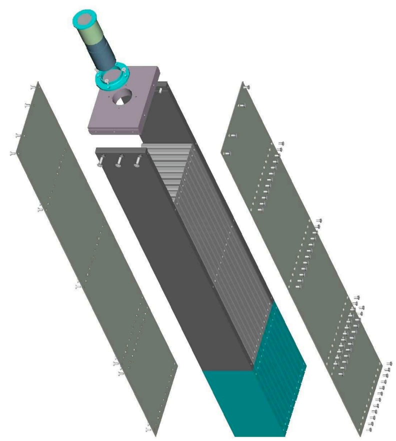

Figure 8. Exploded view of ATLAS ZDC module with fibers and PMT removed.

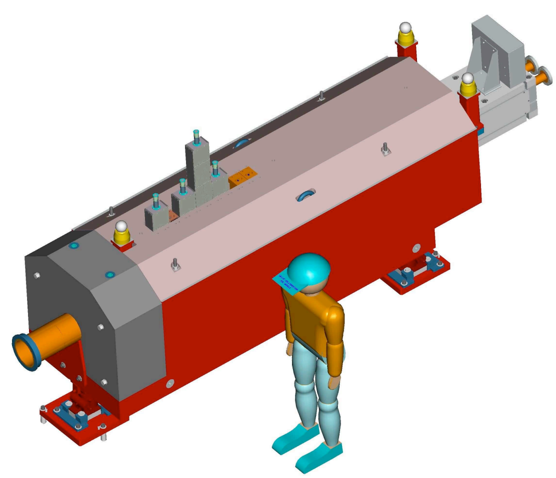

Figure 9. Installation of ATLAS ZDC modules in the TAN. The ion chamber Lumi monitor is in place after the first module. In this view 4 modules are seen to fit however we plan to use only 3 modules.

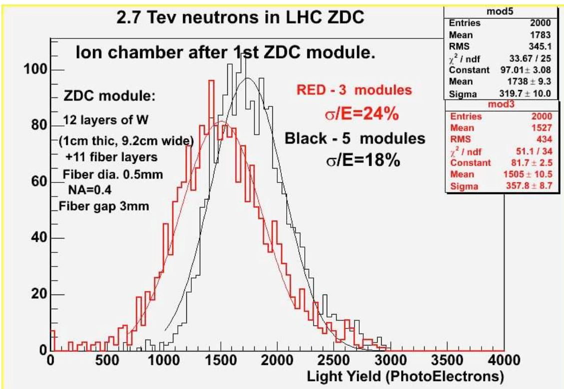

Figure 10. Simulated response of the ATLAS ZDC with 3 modules, the lumi module in place after the first module and high numerical index fiber (NA=0.4).

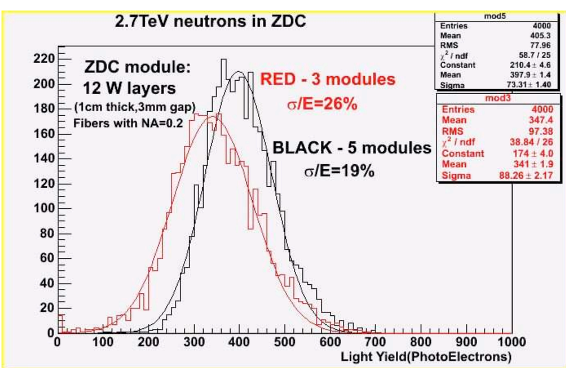

Figure 11. Same as above but using lower numerical aperture fiber (NA=0.2).

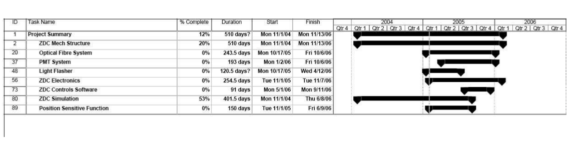

Figure 12. Top level view of the ATLAS ZDC project..