Final Scientific/Technical Report

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Name of Recipient: The University of Iowa

Project Title: "Forward Angle Physics at CMS"

Name of Principal Investigator: Prof. Yasar Onel

Authorized Distribution Limitation Notices: None

EXECUTIVE SUMMARY

CMS will be used to study the reaction products from nuclear collisions of lead with lead at energies of 1100 TeV and also collisions between lighter elements. CMS is a huge detector array at the LHC (Large Hadron Collider), now under construction at CERN in Geneva, Switzerland. The emphasis in this work will be on the far-forward angles (close to the beam line) which has the highest density of products and for which the Univ. of Iowa group has made major contributions to the design and construction of the detectors (CMS-HF, CMS-ZDC). With a detailed knowledge of all of the forward detectors, this group is uniquely prepared to distinguish real physics from effects caused by peculiarities of the detectors. The work included finishing the detectors and getting them into operation and preparing to study data after the LHC restarts in 2010. The Iowa group also continued to develop improved detectors for use with upgrades to CMS and for other applications.

The available energy is almost 30 times that from gold + gold at the present RHIC facility. The new energy regime will open a new window on hot and dense matter physics. The higher energy lengthens the lifetime of a quark gluon plasma and provides additional probes for studying this new form of matter. For example, there is abundant production of jets and heavy quarks with a large cross section for J/ψ and Υ production. The three states of the Υ are clearly resolved by CMS. The different "melting" for members of the Υ family provides information about the nuclear medium. The much wider range of Q^2 and x allow a major extension of the measurements at RHIC.

This large increase in energy provides more than just an extension of RHIC results to higher energy. It is expected to reveal a wealth of new phenomena. This will be the first time that sufficient energy is available to produce in the laboratory the strange and poorly understood objects found in high-energy cosmic ray events. The largest system available in cosmic rays is iron on oxygen. Lead on lead is totally new.

It is only possible to record a small fraction of the output of CMS. With its intimate knowledge of the forward detectors, the Iowa group needs to have a part in decisions about the selection of events to be saved. Otherwise, events that should have the highest priority may be discarded at the trigger level and lost forever.

Iowa CMS Effort

The University of Iowa CMS group has had a major role in the construction of CMS and expects to have a major role in its operation. Professor Y. Onel joined the CMS project in March 1994. We were prompted to join CMS by the exciting physics prospects it offers in high energy and nuclear physics. The University of Iowa (Y. Onel) and Fairfield University (D. Winn) jointly proposed quartz fiber calorimetry for the CMS HF in January 1994 after prototyping the quartz fiber calorimetry through SSC GEM closeout funds. Since joining CMS the Iowa group has taken on important hardware commitments. These relate to the physics we are interested in and draw upon expertise gained from previous work on quartz fiber technology R&D and laser calibration studies for the SSC/GEM project. In 1996, we built an HF-EM prototype module, ran the overall test beam effort, and a new module Raddam 98 was designed and built at Iowa in 1998. We have also led the design, engineering, and manufacturing of the first CMS HF module; the so-called preproduction prototype (PPP1) toward the end of 1999. We also have major management responsibilities for the CMS project. Y. Onel has been the US Coordinator for HF and is the Project Manager for the PMT photodetector project. As part of an ongoing effort, A. Mestvirishvili, a research associate in the Iowa program, has made extensive calculations of the reaction products from both pp and PbPb reactions with special emphasis on the forward angles. He has also contributed during the commissioning phase.

Professors E. Norbeck and Y. Onel joined the USCMS Heavy-Ion group in 2001. They have collaborated/contributed strongly in the construction of detectors in the forward region, conducted physics simulations, and finally to study the data produced by these detectors. E. Norbeck has had extensive experience in intermediate-energy heavy-ion physics making detectors and conducting experiments. Nigel George and Erhan Gulmez have joined in our CMS activity in Iowa City. Prof. George was previously involved in RHIC research at BNL, and Prof. Gulmez was involved in SMC at CERN and SELEX at Fermilab.

US CMS HI Group at Iowa/Iowa Tasks

We have designed, prototyped and constructed parts of the HF detectors. We have designed, built and installed with KU the ZDC detectors. We have submitted a proposal to the NSF-MRI program to build the second CASTOR detector. The CMS detectors in the forward region, HF, CASTOR, ZDC and TOTEM, will provide unparalleled forward coverage at LHC, hence, unique low-x QCD capabilities in pp, pA, AA, hard scattering measurements (jets, high-p_T, DY) down to $x \sim 10^{-6}$, and studies of gluon saturation, CGC, non-linear QCD will be totally accessible.

We have completed:

1. The design and installation of the ZDC. We have worked closely with the Kansas group, and the LHC luminosity group on the quartz fiber baseline. Geometries for the EM and Hadronic sections of the ZDC have been specified. Simulations have been conducted to establish the expected performance. Dimensions have been established which provide for sufficient structural elements and clearances from the TAN walls and Luminosity monitor. Thermal expansion and manufacturing tolerances have been included. An assembled TAN was inspected to verify dimensions. A simple and robust structure has

been designed which mounts the various ZDC components, provides a light-tight enclosure, and provides for attachment to a remote lifting system for removal from the TAN. The lightguide and phototube designs are copied with only minor modifications from CMS HF.

2. We have worked on the evaluation of quartz fiber types and selection of the quartz fiber type for the ZDC.
3. We performed radiation damage studies for the final selection of quartz fiber types at the Iowa Raddam facilities, the CERN-Iowa Raddam facilities, and the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL).
4. We have worked on the purchase of the fibers and establishment of quality control and quality assurance (QC/QA) procedures.
5. We have established QC/QA procedures for the fibers at the Iowa HEP/Optics Laboratory.
6. We have worked on the selection and QC/QA of PMT's and PMT bases
7. We have worked on the development of LED and radioactive source calibration systems for all of the hadronic calorimeters in CMS. This includes the calorimeters in the barrel and endcap, in addition to HF. This work provides us with a unique insight into the operation of these calorimeters.
8. We have designed and constructed an on-line fiber "radiation damage" monitoring system. The University of Iowa group was recently chosen by the HF group to build on-line radiation damage monitors for the HF wedges. The idea is to inject monochromatic light into the fibers and use the reflection of light at the entrance and at the end of the fiber to calculate the radiation damage of fibers in HF operation at LHC. We used a nitrogen pulse laser (337 nm) to inject light into a sample of 2.5 m long quartz fibers of the HF calorimeter. We measured with the HF PMT (Hamamatsu R7525) the amplitude of signals reflected from the two ends of the fiber. We would like to develop this idea further and install a similar device in the ZDC.
9. The ZDC's were tested at the HCAL test beam and the Iowa group participated in these runs.
10. ZDC Installation: Right EM&HAD installed into the TAN. Left EM&HAD was installed in the tunnel. Cable connections were continuously verified during the installation procedure. After all connections were completed, each section was tested and commissioned. All cables and quartz fibers of the laser system were pulled before the start of the ZDC installation. Test and commissioning of the detectors mainly involved HV (high voltage) system tests and LED (light emitted diode) and laser calibrations. Each ZDC section has been calibrated in the test beam. Iowa group has participated in these installations and played a major role.
11. Readout module design for the HAD are being developed at Iowa.
12. A lifting fixture conceptual design has started at Iowa. We will decide soon to carry on or not with this design and construction.

We would have liked to have had a dedicated graduate student to start working in the CMS Heavy Ion group and work on the simulation of HF Jet construction using CMSSW, HF Calibration problems, HF response, energy resolution and eta, phi resolution, and HF Jet Efficiency, but this funding was not available for our group.

Progress

We have received funds from the DOE-Heavy Ion program, subcontract from Kansas University, and University of Iowa, Office of VP of Research, for an R&D program.

CMS zero degree calorimetry – Engineering status report

Completed Tasks: Geometries for the EM and Hadronic sections of the ZDC have been specified. Simulations have been conducted to establish the expected performance. Dimensions have been established which provide for sufficient structural elements and clearances from the TAN walls and Luminosity monitor. Thermal expansion and manufacturing tolerances have been included. An assembled TAN was inspected to verify dimensions. A simple and robust structure has been designed which mounts the various ZDC components, provides a light-tight enclosure, and provides for attachment to a remote lifting system for removal from the TAN. The lightguide and phototube designs are copied with only minor modifications from CMS HF.

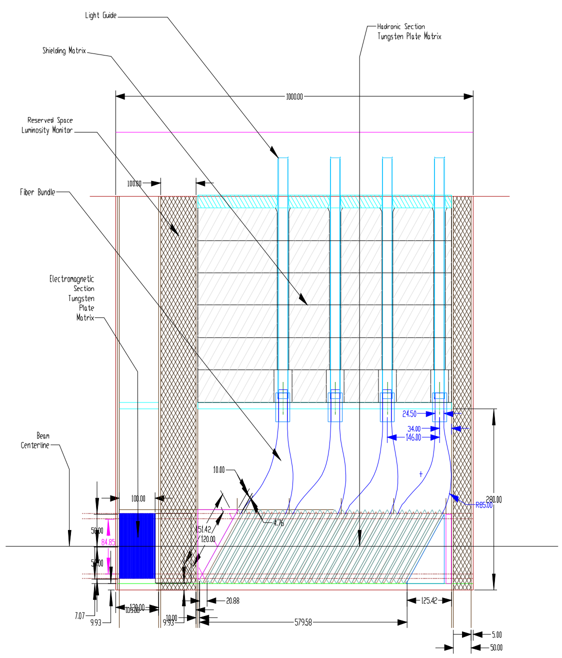

Figure 1. Side view of ZDC.

ZDC simulation studies

A ZDC was proposed for CMS for measuring spectator neutrons and forward photons in the heavy ion and early pp runs. The design consists of an electromagnetic section 22 radiation lengths thick followed by a luminosity monitor and then by 4 hadronic sections, each 1.6

interaction lengths deep. Each section will be read out by photomultiplier tubes. Although principally designed for measuring the geometry of heavy ion collisions, the ZDC will also help with tuning the beam and measuring the luminosity for both PbPb and pp running. The ZDC will also help the rest of CMS make energy flow measurement for PbPb and pp collisions. We have used the GEANT4 Monte Carlo simulation program to help determine ZDC design parameters. The choice of tungsten plate thickness and the quartz fiber packing fraction are two important parameters. They determine the performance of this detector, and therefore an optimized decision is essential. We have studied the light yield and energy resolution by varying the tungsten plate thickness and the quartz fiber core diameter. GEANT4 Monte Carlo simulations for 1.0 cm thick tungsten plates interleaved with 600 micron core diameter quartz fibers at 45° with respect to the beam direction have been completed. The effects of the light attenuation in the quartz fiber were also simulated. The quantum efficiency characteristics of the photomultiplier tube (PMT) as a function of photon wavelength and the light guides between the fiber bundles and the PMTs were simulated too.

Photoelectron Response: The Čerenkov photons in the simulation are generated with a custom Čerenkov code implemented in the GEANT4 package (see Progress Report FY06, http://omega.physics.uiowa.edu/HI/talks/ProgressReport-06_new.pdf). The attenuation in the fibers as well as in the light guides connecting the fibers to photomultiplier tube is also simulated. The quantum efficiencies of the photomultiplier tubes were also taken into account. We have determined the effects of the quartz packing fraction on the light yield and on the energy resolution. We have also studied the effects of the tungsten and quartz ribbon angle on the same detector characteristics. The energy resolution constant term is insensitive to packing fraction at the TeV level and is approximately 10%. The stochastic term is dependent on the packing fraction which determines the amount of light generated and collected in the calorimeter. We ran our simulation with 500 GeV, 1 TeV, and 2 TeV neutrons and 100 GeV, 200 GeV, and 500 GeV protons. Each simulation has 500 events. At the TeV scale, we have not observed a significant difference in the resolution with 1 cm thick tungsten plates instead of 0.5 cm thick plates. It is also seen that at TeV energy scales, the event to event fluctuations flatten out and the resolution is completely dominated by the constant term.

Results from *post situ* quartz fiber neutron irradiations

In order to measure the degradation of quartz optical fibers under a high background radiation, which is expected to be present in the CMS forward calorimeter at the LHC, the fibers were irradiated with pulses of high-energy neutrons produced by the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory.

Radiation hardness of quartz fibers irradiated with 24 GeV protons

Studying the effects of radiation on quartz fibers is necessary if we would like to use them in high radiation level environments in CMS. The U. of Iowa CMS group investigated the radiation hardness of different types of quartz fibers in association with Turkish HF groups. The results of attenuation measurements of quartz fibers (0.3 and 0.4 mm core diameter) irradiated with 500 MeV electrons up to 100 Mrad were already published [26]. To further our knowledge of radiation damage of the quartz fibers (quartz-plastic 0.6 mm core diameter) we initiated a high level of irradiation with 24 GeV protons at CERN. About 4.6×10^{16} protons/cm^2, corresponding to a dose of 1.3 Grad (i.e. about 13 years of HF operation in the hottest tower!), were sent onto the 1.20 m of quartz fibers. It was the first time that one achieved such a high irradiation dose in quartz fibers.

Physics simulation in CMS

We have performed some simulations for the HF detector regarding impact parameter determination since study of events with different centrality in heavy ion collision is important for heavy quarkonium, hard jets and high-mass dimuon production processes as well as Higgs boson production in the electromagnetic field of two colliding nuclei.

Progress

ZDC Readout Modules – EM & HAD Design

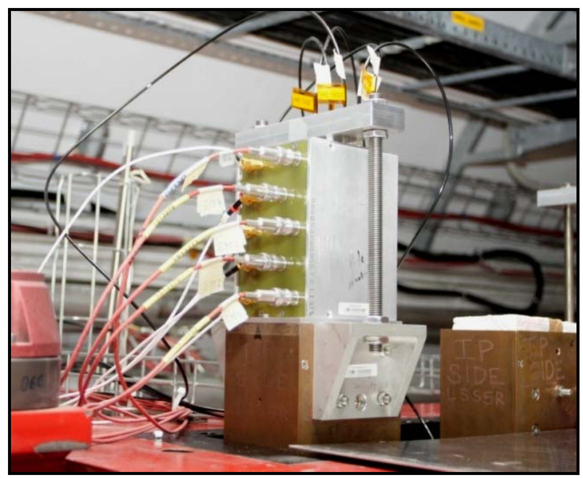

Figure 2**.** PMT read-out box of the EM section.

Figure 3. EM and HAD sections in TAN.

The design was completed for the Readout Boxes (R/O) of the ZDC Hadronic modules. Electromagnetic modules were completed in the previous year. The R/O modules complete the enclosure of the ZDC, forming a sealed, light-tight unit. R/O modules support 4 PMTs, high voltage bases, connector for light calibrations (laser or LED) and a gas fitting to provide a helium-excluding inertion atmosphere around the PMT.

Read-out electronics

There are a total of 18 readout channels for the two ZDCs. Photomultiplier tubes (PMT) are used as photo detectors. The PMT is an 8 - stage Hamamatsu R7525 phototube with bi - alkali photocathode, with average quantum efficiency for Cherenkov light of approximately 10%. The resistive chain high voltage base (ratio "B") is optimized to achieve a high gain and the maximum dynamic range of linearity. The high-voltage power supplies are mounted in a rack in a NIM crate that resides in the counting room. These units will be controlled and monitored via HCAL slow controls. The PMT's base has two connectors: a coaxial signal output connector and a SHV high voltage connector. The PMT and base are housed in a shielding enclosure, so called PMT read-out box. A photograph of the EM section PMT read-out box is shown on Figure 2.

Zero Degree Calorimeter installation

Right EM and HAD sections of one ZDC were installed. Both detectors went smoothly into the TAN. Electronics for the EM and HAD sections were arranged, labeled, and powered on in USC55. All items were bar-coded and everything to go into the tunnel was engraved.

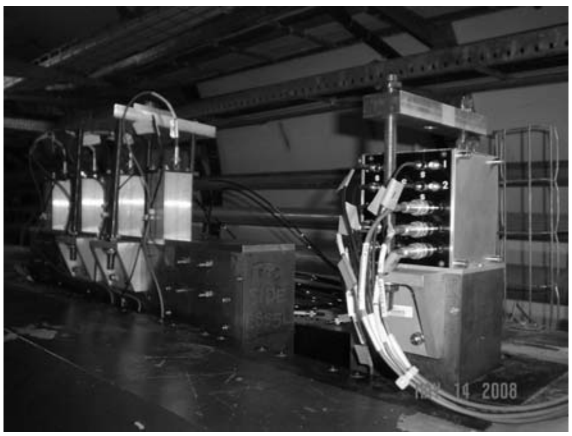

Figure 4. ZDC installed in sector 4-5 of the LHC.

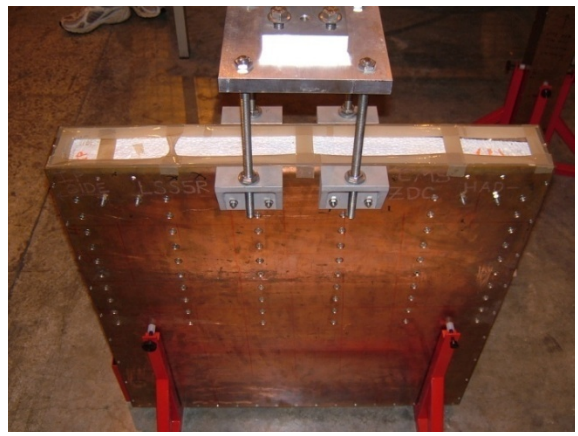

Figure 5. ZDC HAD readout modules.

Design was completed for the readout boxes of the ZDC EM and HAD module. The readout modules complete the enclosure of the ZDC forming a sealed light tight unit. Readout boxes support four PMTs, high voltage basis, connect for light calibration (laser and LED) and gas fitting to provide a helium excluding inertian atmosphere around the PMT.

Progress

Conceptual design was developed for the removal of the ZDC from the TAN and insertion into a shielding garage.

Paul Debbins has worked on the engineering aspect of this project:
1) First (of 2) CMS Zero Degree Calorimeters is assembled at CERN and Test Beam studies performed; 2) Second ZDC is assembled and Test Beam studies completed; these test beams were conducted with the final configuration of Tungsten plate and Quartz fiber absorber/detector assembly, using temporary modules to hold PMT and electronics; 3) ZDCs installed with temporary R/O modules into IP5 left and right TANs, 4) Final Readout modules assembled and installed onto both ZDCs, and 5) Calibration laser fibers attached to ZDC modules, electrical tests performed, electronics rack developed, and work to integrate ZDC signals into CMS DAQ and Trigger undertaken (Alexi did this for our group).

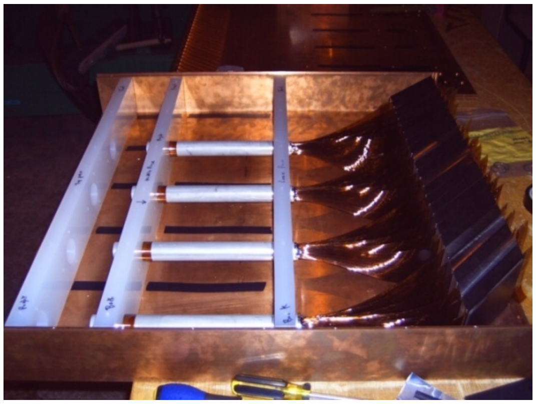

Fig. 6. The lightguides, quartz fiber bundles, and tungsten plates in the interior of a ZDC Hadronic module during assembly at CERN.

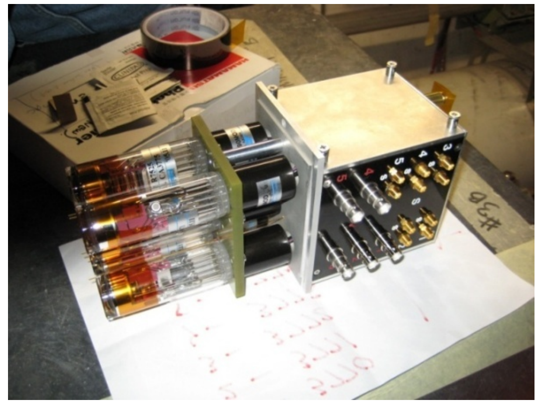

Fig. 7. Completed ZDC electromagnetic section readout module ready for installation.

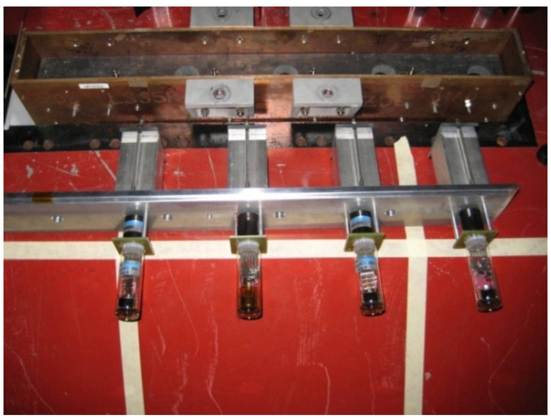

Fig. 8. ZDC Hadronic section readout module being installed onto the absorber/ detector assembly installed in the TAN.

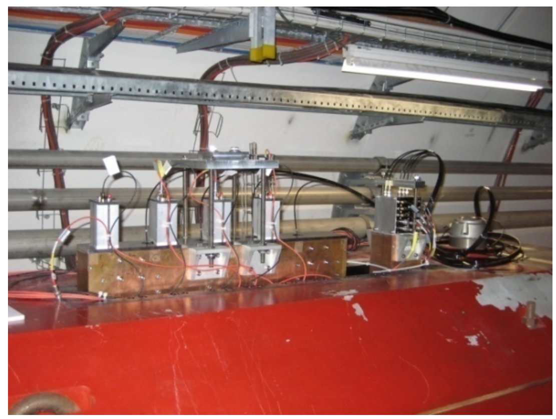

Fig. 9. ZDC Hadronic (left) and Electro-magentic (right) sections installed in CMS (minus side) TAN.

CMS ZDC Remote Handling Crane

At periodic intervals the ZDC must be removed from the TAN. These occur during vacuum pipe bakeout, which has higher temperatures than the ZDC can withstand, and during high luminosity p-p beams, which deposit too much energy in the ZDC for the quartz fibers to tolerate. During the high luminosity p-p runs the ZDC must be replaced by a set of copper bars to replace the mass of the ZDC in order to absorb the radiation that would otherwise induce quenching in the following superconducting magnet. The CERN Underground Transport and Radio Protection groups have determined that the level of activation expected in the TAN region is too great to allow manual human intervention to remove and install ZDC and copper bar elements. In order to operate the ZDC in beams, a remote handling system has been mandated, as well as shielding storage containers to hold the elements not currently installed inside the TAN. The University of Iowa has finished the design work. This remote handling system for CMS passed a review by CERN personnel. University of Iowa is the principal architect and designer of the CMS ZDC and Remote Handling systems. We will be responsible to provide expertise for maintenance of the

ZDC (such as PMT replacement) as well as maintenance and operation of the Remote Handling System.

- Both ZDCs were commissioned with LED/Laser systems before the LHC start-up.
- ZDC saw beam splash events during the first LHC beam.
- Iowa-HEP post-doc. Alexi Mestvirishvili has solved overflow reflection and pedestal problems in the ZDC readout system. The signal splitting was redone.
- Alexi did retiming of the ZDC with laser signals.
- The integration of the ZDCs into the HCAL readout/DQM/DSC has started (ZDC is in the HF readout partition).
- The HF detector is fully calibrated and commissioned and tested with cosmic muons through CMS GLOBAL and CRUZET runs and HF saw beam events and beam halo events.

Physics Simulations

- Y. Onel initiated two simulation studies through new graduate students in the HF group. This resulted in two CMS analysis notes.
- The generator-level studies of the capabilities of the HF and CASTOR calorimeters to determine the centrality of the events in Pb-Pb collisions at $\sqrt{s}$ = 5.5 TeV collisions in CMS were studied (CMS AN-2007/054 Sertac).

PRODUCTS DEVELOPED UNDER THE AWARD

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"Measurement of transverse energy flow in a large η range and forward jets at LHC at $\sqrt{s}$ =900 GeV and 2360 GeV, CMS AN-2010/023 (2010).

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