Attachment no. 2b to the "Wniosek o wszczęcie postępowania habilitacyjnego"
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Summary of professional accomplishments

Contents

1 Personal data

First and last name: Grzegorz Grzelak
Date of birth: 1 April 1966

2 Education

- Master of Science in Physics, Faculty of Physics, University of Warsaw
  title: *Badanie własności kalorymetru BAC detektora ZEUS*
  (*Study of the properties of the Backing Calorimeter for the ZEUS detector*)
  supervisor: dr Roman Walczak
  year: 1990
- Doctor of Philosophy (PhD) in Physics, Faculty of Physics, University of Warsaw
  title: *Production of Intermediate W and Z Bosons in ep Interactions at 300 GeV Centre of Mass Energy (Experiment ZEUS at the HERA Accelerator)*
  supervisor: dr hab. Jacek Ciborowski
  referees: prof. dr hab. Danuta Kisielewska, prof. dr hab. Krzysztof Doroba
  year: 1999

3 Employment

1. **1 X 1990 – 30 IV 1991**, Laboratory of Crystal Growth, Warsaw
2. **1 V 1991 – 30 IX 1991**, Faculty of Physics, University of Warsaw, technician
3. **1 X 1991 - 30 IV 2006**, Faculty of Physics, University of Warsaw, assistant lecturer (sabbatical 1 II 2002 – 31 I 2005)
4. **1 II 2002 – 31 I 2005**, Faculty of Physics, Oxford University, post-doctoral research assistant
5. **1 V 2006 - today**, Faculty of Physics, University of Warsaw, associate professor (adjunct)

4 Academic career

4.1 Period related to master's and PhD thesis

In 1988, in the fourth year of my academic study, I joined Warsaw Backing Calorimeter (BAC) group building the BAC detector for the ZEUS experiment at the HERA accelerator constructed in Deutsches Synchrotron laboratory (DESY) in Hamburg. I started with the analysis of the calibration data obtained using the BAC prototype at the test beam in CERN in Geneva. For the purpose of my master's thesis I built in Warsaw a test stand composed of one hundred proportional chambers dedicated to the investigation of BAC analog preamplifiers and shapers and testing the prototype of FADC board using cosmic rays. The scope of my master's thesis covered also the investigation of chambers uniformity using radioactive strontium source and the study of the gas gain and chambers resolution as a function of high voltage using iron ^{55}Fe calibration source. In 1990 I defended the master's thesis titled: "Study of the properties of the Backing Calorimeter for the ZEUS detector".

Since 1990 I'm a member of the ZEUS collaboration. During the construction of the detector I participated in the installation of the BAC calorimeter in the experimental hall, for instance in the project of its cabling, including the distribution of power supply, signal and monitoring cables. At early stage I joined also the BAC off-line software team developing the reconstruction and Monte Carlo simulation codes for Backing Calorimeter. I worked on the noise suppression procedures based on the FADC signal shape analysis. My responsibility was also to develop the indexing scheme of BAC towers used to translate the hardware addresses onto the physical location. I contributed also to the definition of BAC geometry used in the off-line analysis.

In 1992 I joined the analysis effort of Exotics Physics working group dealing with rare phenomena and searching for processes beyond Standard Model. During this period I performed the first in the ZEUS experiment analysis of the production of intermediate W and Z bosons with subsequent hadronic decay to high energy jets. For the purpose of this analysis I incorporated into the ZEUS Monte Carlo framework the EPVEC [1, 2] generator describing the production of W/Z bosons in electron–proton (ep) interactions. For instance, I included the hadronization processes of final states quarks using the JETSET [3] model. This study was also related to the detailed investigation of the QCD background processes with high transverse energy, which I performed using PYTHIA [4] and HERWIG [5] generators. As HERA accumulated sufficient statistic of data, the analysis allowed to determine the upper limits on the cross section value for the production of W and Z bosons in ep collisions at HERA (including statistic and systematic uncertainties): $\sigma_W < 9.9$ pb, $\sigma_Z < 3.3$ pb in agreement with the predictions of Standard Model of about $\lesssim 1$ pb. These results were presented in my PhD thesis titled: *"Production of Intermediate W and Z Bosons in ep Interactions at 300 GeV Centre of Mass Energy (Experiment ZEUS at the HERA Accelerator)"* [6].

In 1994 I performed the configuration of the cluster of Silicon Graphics workstations at the Faculty of Physics in Warsaw and installed the "production" software for Monte Carlo event generation in ZEUS experiment (the "funnel" system). Till 1998 I was responsible for the running of this system.

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At the beginning the generated events were being sent back to central archive at DESY using DLT mass storage tapes. As the network bandwidth was increased they were substituted by the Internet transfer. During this period I participated also to the developing of the muon identification procedures for the Backing Calorimeter.

4.2 Period after PhD and present academic activity

After finishing the PhD thesis I undertook the decision to continue my scientific activity in the ZEUS experiment and became the leader of the BAC muon trigger project. This project is described in more details in the next chapter (Presentation of the scientific achievement).

In years 1999–2002 I was working also as the BAC on-line expert and performed the duties as the official BAC group 'on-site' representative at DESY. This period coincided with the long shutdown of the HERA accelerator (2000–2001) devoted to increase its luminosity and to deliver the polarized electron beam to the H1 and ZEUS experiments. That period was also utilized for the upgrade of the detectors working at the HERA collider. I was supervising the project of BAC "revitalization" aiming to increase its reliability in view of the planned implementation of BAC muon trigger. The scheduled works were related to the improvement of the BAC low voltage power supply distribution, constructing of the cooling system for the hit-readout electronics and repairs of faulty shapers.

Apart from the activity directly related to the BAC muon trigger I worked also on the design and programming of BAC charge injection system (pulser), and on the activation of the new element of the ZEUS data acquisition protocol (*"Fast Clear"* signals) implemented for HERA-II period in order to handle the increased event rate. During the above work an unexpected disfunction were discovered related to the GFLTBI board (GFLT Board Interface) acting as the interface between BAC and the GFLT (Global First Level Trigger) processor. The GFLTBI module was unable to handle certain sequence of *Accept – Busy – Fast Clear* signals leading the lost of synchronization of the BAC calorimeter with the rest of experiment. The final solving of this problem required to design a new GFLTBI board constructed by using programmable FPGA circuits.

Next project, performed parallel to the implementation of the BAC muon trigger, was the improvement of the BAC diagnostic systems. I coordinated further development of the off-line DQM (Data Quality Monitoring) and supervised the design of the real-time monitoring system (on-line DQM) generating alarms for the on-call experts. My original project was the autonomous diagnostic program `BAC_DIAG` collecting data of the detector condition, helping to synchronize the BAC muon trigger signals (adjusting timings) and providing automated generation of the detector configuration for the purpose of the data acquisition programs (setup files). All this elements were described in more details in the habilitation monograph.

In the years 2002–2005 I was employed as the Post-doctoral Research Assistant at the Oxford University (Faculty of Physics). I was sharing my time between two projects: *(i)* The Linear Collider Alignment and Survey (LiCAS) dealing with the precise alignment of the future linear collider and *(ii)* the data analysis collected by the laser alignment system for the Micro-vertex Detector (MVD) in the ZEUS experiment. This system was constructed by the Oxford ZEUS group which was also responsible for his running. Being still engaged in the ZEUS experiment and performing frequent trips to DESY for the data taking shifts allowed me also to keep in touch with my parent group and to continue the work on the BAC muon trigger, and participate to the commissioning of its first level hardware.

Project LiCAS in years 2002–2005 performed R&D studies on the prototype of the novel metrology instrument dedicated to align and monitor the mechanical stability of the elements of future e^+e^- linear collider. According to its concept, automated, self-propelled device (a "train") called RTRS (Rapid Tunnel Reference Surveyor) [7, 8] mounted on the rail placed along accelerator tunnel and composed of several modules ("cars") could precisely measure the position of reference markers located on the tunnel wall. The position of each marker should be measured several times by different cars of the train. Such redundant (overlaping) measurement allowed for the reconstruction of the relative global positions of all markers by performing a simultaneous fit to all its positions reconstructed in local frames at each train stop. As a result of such procedure a global reference frame connected with the wall reference markers were established. It could be updated on the regular basis to account for the geological instability of the tunnel ground. In the next step the position of all accelerator elements were determined (and possibly corrected, if needed) with respect to the "tunnel frame". Each module (car) was equipped with two sub-systems dedicated to the interferometric absolute distance measurement (using FSI technique: Frequency Scanning Interferometry) [9, 10] and the Laser Straightness Monitor (LSM) used to define reference straight line ("laser ruler"). The FSI system performed the distance measurement between the cars at each train stop in front of wall markers and the distance measurement from the cars to the wall markers. The LSM system was composed of 4 CCD cameras installed at each car. Using semitransparent beam-splitters the laser beam was directed on the CCD surface. By using proper configuration of CCD cameras the system was sensitive to the translation and rotation around two axes perpendicular to the laser beam line. The advantage of such a system comparing to traditional "open air" geodesy was the superior precision obtained by eliminating uncertainties related to the light refraction in air (the main laser beam of the LSM system was conducted inside vacuum pipe located along the train). Also the time needed to establish a reference frame was substantially reduced.

In the LiCAS project I was responsible for the analysis of the error propagation during the construction of a reference frame along the tunnel. In my calculations I was using software package SIMULGEO [11] designed to model the opto-geometrical systems and performing ray tracing between its various sub-components. Its allowed also for numerical (matrix based) analysis of error propagation for the positions and angles of all its elements, including their correlations due to the placement on common mechanical (and usually hierarchical) support. In parallel, I was developing my original approach for the error propagation based on the Monte Carlo technique and the "random walk" model. The considered alignment process is similar to the construction of a very long straight line using many shorter sections plotted along much shorter ruler. In both cases I got consistent results presented on several international conferences related to the accelerator alignment (IWAA series: International Workshop on Accelerator Alignment) and on conferences devoted to the project of future linear accelerators [13–18]. The results confirmed the possibility to obtain the precision of coaxial placement of the accelerator elements with the precision of $\mathcal{O}(200)$ μm (stat.) over 600 m tunnel section meeting the specification of the considered (that time) TESLA project [12]. The application of the Monte Carlo technique for the random walk process in conjunction with the SIMULGEO package allowed also to construct realistic model for the propagation of the systematic errors originated from the uncertainties of the calibration constants of the considered device. The conclusions derived at this stage suggested the need of significant increase of the distance between neighbor cars in the final RTRS train.

During my stay at the Oxford University I was also involved in the analysis of the data collected by the laser alignment system for the MVD detector. The Micro-vertex detector was a new instrument installed during the upgrade of the ZEUS detector for the HERA-II period. The Oxford group designed and constructed its alignment system and was responsible for its operation. It was composed of six laser beams located on the outer surface of the MVD barrel support. Along each laser line seven pairs of semitransparent silicon strip sensors were located. The strips of each pair were crossed at 90 degree allowing for the measurement of two spacial coordinates. Data acquisition for this system was performed on regular basis in the breaks between the cycles of the HERA accelerator fillings. It delivered a rich data set related to the mechanical stability of the MVD detector. Using long-term measurements of the reference laser beam spot positions, the misplacement and rotations of the MVD relative to the Central Tracking Detector (CTD) were deduced. The data allowed to establish the "periods of stability" of the MVD detector. For each such period a set of calibration constants were generated allowing for precise matching between MVD and CTD detectors. The results obtained in this analysis were presented in two papers published in the "Nuclear Instruments and Methods" journal documenting the construction and performance of the MVD detector [19, 20].

After return from Oxford in 2005 I was continuing the collaboration with the Oxford LiCAS group. For instance, in that period the analysis of the systematic effects described above were performed and presented at the IWAA-2008 conference. At the same time I joined also the newly established Warsaw group working on the next generation of silicon sensor pixel detectors (MIMOSA) for the Micro-vertex detector the future linear collider in the framework of the EUDET project. This activity was related to the analysis of the data collected at the DESY electron test beam, for instance, the shapes of pixel clusters induced by electrons penetrating at different angles with respect to the surface of the silicon sensor were analyzed. This issue has an important practical application as it can be used to select deposits produced by the particles emitted from the interaction point and suppress the deposits of background particles induced by the beamstrahlung process. The above study was summarized in the article published in the "Nuclear Instruments and Methods" journal [21].

After the post-doc training I was still involved in the work of the ZEUS collaboration, leading the BAC group to the full implementation of BAC muon trigger on its all three levels. Till the end of data taking in June 2007 I performed the duties of on-line expert, overseeing the data taking, monitoring the quality of data and contributing to the service of the BAC detector. During the period of the full functionality of all three levels of the BAC muon trigger, the Backing Calorimeter collected data corresponding to the integrated luminosity of about 200 pb^{-1} (60% of the integrated luminosity collected by the ZEUS experiment during HERA-II period).

From July 2007 till the end of 2008 I was responsible for the decommissioning of the Backing Calorimeter and the dismantling of its equipment including over 5000 aluminum proportional chambers and its electronics systems. I also organized a transportation of the fraction of the BAC chambers and its electronics to the student's laboratory at the Faculty of Physics in Warsaw.

Since then I have been participating in the ZEUS data analysis. My scientific activity focuses on processes with muons in final state, in particular on the exclusive production of vector mesons in ep interactions. In order to fully incorporate into the analysis the muon data collected with the BAC calorimeter I determined its muon efficiency for consecutive data taking periods for three trigger levels and for off-line reconstruction using elastic production of muon pairs. The obtained results were presented in the dedicated chapter of the habilitation monograph. I contributed also to the *"Data Preservation"* [22] programme conducted in the ZEUS experiment. The goal of the *"Data Preservation"* project is to establish the long-term framework for off-line analysis and data storage format allowing to continue the data analysis without having detailed access to the knowledge and experience accumulated by the experts during full collaboration activity. For the purpose of this project the ZEUS collaboration decided to change the format of data storage from ADAMO [23] and PAW ntuples in favor of ROOT [24] ntuples. As a contribution of BAC data to this project I prepared a procedures creating new data structures containing the information from BAC position readout (muon wires segments and associated energy clusters) used by the BAC muon reconstruction programmes. These data were incorporated into the new ZEUS archive (so called ROOT Common Ntuples) containing the final set of data (and Monte Carlo events) obtained by ZEUS experiment during HERA-I and HERA-II periods.

As a chief editor I was responsible for the preparation of a publication related to the exclusive production of Υ mesons in the ZEUS: "Measurement of the t dependence in exclusive photoproduction of $\Upsilon(1S)$ mesons at HERA" [33]. For the purpose of this publication I performed also a supplementary analysis required by referees related to the resolution of the reconstruction of the kinematic variables. In this analysis for the first time the slope parameter b for the t variable distribution ($\sim \exp(-b|t|)$) was determined for the diffractive process of Υ meson production, where t is the four-momentum squared at the proton vertex. Obtained value $b = 4.3^{+2.0}_{-1.3}$ (stat.)$^{+0.5}_{-0.6}$ (syst.) GeV^{-2} was in agreement with QCD based theoretical calculations and in agreement with previous measurements for other heavy vector mesons. The value of b parameter in the optical model can be used to estimate the so called gluonic proton radius $R_\mathrm{p}^\mathrm{gluons} \approx 0.6$ fm. Interestingly, this value is smaller than the electromagnetic proton radius ($R_\mathrm{p}^\mathrm{em} \approx 0.8$ fm) suggesting more dense packing of gluons inside proton then the packing of electrically charged quarks. I presented the results related to the production of vector mesons on several international conferences, on behalf of ZEUS and together on H1 and ZEUS collaborations, including invited talks [25–28]. I shared also my experience on vector meson production with students and PhD students performing data analysis at DESY, participating in years 2013–2015 in weekly skype meetings dedicated to their ongoing analyses.

5 Presentation of the scientific achievement

in accordance with Polish regulation Art. 16. ust. 2 Ustawy z dnia 14 marca 2003 roku O stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (Dz. U. nr 65 poz. 595 z pniejszymi zmianami).

As the scientific achievement I present the monograph titled:

Mionowy ukad wyzwalania kalorymetru BAC
(The muon trigger system of the Backing Calorimeter)

published by "Wydawnictwa Uniwersytetu Warszawskiego" (Warsaw University Press) , Warsaw 2017, ISBN 978-83-235-2735-0. I am the sole author of this monograph. The presented monograph introduces the project of implementation of three level muon trigger system for the Backing Calorimeter (BAC) working in the ZEUS experiment at the electron–proton accelerator HERA in DESY (Hamburg).

The construction of the Backing Calorimeter [29] performed at the beginning of the last decade of XX century was the biggest hardware involvement of Polish research groups in the history of high energy and particle physics experiments. It was conducted by the collaboration of Faculties of Physics from University of Warsaw and AGH University of Science and Technology in Kraków. Polish team was responsible for the project of this detector, construction of the prototype and its tests on the test beam in CERN (Geneva). Next, at the University of Warsaw a mass production of six thousand proportional aluminum chambers was performed. The chambers were subsequently installed in the ZEUS detector in Hamburg. The team from AGH University in Kraków was responsible for the gas system of the detector delivering the mixture of argon and carbon dioxide for the chambers. Polish engineers were also responsible for the project and construction of readout electronics for the Backing Calorimeter: its analog and digital components. Physicists and IT specialists from Warsaw designed and implemented the real-time software for data acquisition (on-line) and off-line programmes used for event reconstruction and Monte Carlo simulation. Over the period of 15 years (1992–2007) the BAC crew was controling the data taking process, monitoring the quality of collected data and performing service repairs.

The main motivation for the construction of the Backing Calorimeter was the measurement of high energy hadron cascades (jets) leaking out of the Central Calorimeter (CAL) [30]. BAC was also capable to supplement the muon identification in addition to dedicated muon chambers installed in the ZEUS experiment. The ZEUS experiment was equipped with high resolution, compensating uranium calorimeter described in habilitation monograph. Its depth, expressed by absorption lengths, was sufficient to measure for 90% of jets of maximal kinematically allowed energy the 95% of their energy. The remaining fraction of energy leaking out of CAL was foreseen to be measured in BAC.

As it was described in more details in the monograph, the experience gained during the first period of data taking at HERA-I phase (till 1999) has verified the above predictions. Where bigger statistic of data was accumulated, the expected number of evens with the significant leakage into the Backing Calorimeter was not observed. Looking back to the design phase of the experiments at HERA collider one have to conclude that the theoretical predictions, available "on market" at that time in the form of Monte Carlo simulations underestimated the role of gluons. Their contribution to the parton shower evolution (transition from partonic to hadronic final state) was much more significant, leading to the energy sharing of leading quarks into bigger number of less energetic, thus less penetrating, particles. In consequence, at the end of HERA-I phase the Backing Calorimeter was the biggest component of the ZEUS detector having the smallest contribution to its physics programme. This fact induced the necessity to define anew the role of the BAC detector to better utilize its research potential.

In 1999 the author of the presented here monograph defended his PhD thesis related to the production of intermediate W and Z bosons in ep interactions at the HERA collider. This coincided with the long technical shutdown of HERA devoted to the accelerator and detectors upgrade. The author decided to continue his scientific engagement in the ZEUS experiment and was seeking for the new research activity. The experience accumulated during the PhD work brought him to the idea of supplementing the Backing Calorimeter with its own trigger focused on muons. The location of the Backing Calorimeter far from the interaction point made this detector well suited for the muon identification and created the chance to increase the muon sensitivity of the whole ZEUS experiment. This capability was created by the newly installed positional (hit) readout. The BAC detector, equipped with muon trigger electronics, could increase the overall ZEUS efficiency for final state muons, especially in the areas not covered by muon chambers: in the bottom of the iron yoke and at the edge between forward muon chambers (FMUON) and barrel muon chambers (BRMUO).

Since 1999 till the end of data taking in 2007 the author was leading a team of physicists, engineers and technicians as well as students and PhD students involved in this project. Changing the profile of the Backing Calorimeter towards its application as a muon detector and including it into the global trigger system of the ZEUS experiment was an ambitious challenge. First of all it required the increase of the reliability of the BAC detector. For the purpose of its overhaul conducted during the HERA shutdown (2000-2001) the author prepared detailed plan defining the tasks and responsibilities of all participating persons. Apart from coordinating the project, the author was also involved in the work on the upgrade of the low voltage power supply distribution and the cooling of hit-readout electronics (hitboxes). The author designed also the database for Backing Calorimeter and loaded it with all necessary data related to all detector sub-systems including the hierarchical relations between various elements. The author worked also on the specification of the diagnostic programs for BAC (on-line and off-line data quality monitoring). Its original contribution was the implementation of autonomous (stand-alone) diagnostic programme `BAC_DIAG`. He also contributed to the specification of charge injection system (pulser), its testing and programming. The planned shifting of the "center of gravity" of BAC application from calorimetric measurement towards muon identification required also to develop new reconstruction routines available to the users in the ZEUS collaboration performing physics analysis (package `MuBAC`).

Parallel to the project on the "revitalization" of the Backing Calorimeter the author was also participating to the specification of the new FLT (First Level Trigger) boards and the GFLTBI board and further tests in the electronics lab and installation on the detector. He contributed also to the development of the software library for BAC FLT boards created in the transputer programming language OCCAM. He coordinated and contributed to the synchronization of BAC FLT signals with the global GFLT processor including the implementation of the *Fast Clear* protocol. Next, he coordinated the connection of BAC to the global second level of the ZEUS trigger (GSLT). Finally, his original project was the design and implementation of software for the third level BAC trigger, successfully incorporated onto the ZEUS TLT farm.

The hardware and software of the Backing Calorimeter muon trigger was described in a separate article [31] and in the habilitation monograph. In the following a short description of the basic idea behind BAC muon trigger is presented. The active component of the Backing Calorimeter were aluminum proportional chambers equipped with anode wires and cathode planes (pads) delivering charge signal related to the ionization particles passing through the gas mixture (argon and carbon dioxide) inside chambers. BAC was composed of ~ 5200 chambers grouped into layers containing altogether about 40 thousand anode wires and 45 thousands cathode planes. This structure was further divided into bigger units called towers (about 200 anode wires towers and about 1500 pad

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towers). In the plane perpendicular to the wires their pattern was forming a two dimensional grid allowing to reconstruct the trajectory of passing particle. Third spatial coordinate was reconstructed by using cathode planes located along wires.

The ZEUS detector was equipped with three level trigger system of increasing selectivity. All active elements of the detector (sensors) were connected via amplifiers to the analog-to-digital converters. The process of data digitalization was continuous and synchronized by 10 MHz clock of the HERA accelerator defining also the bunch crossings of ep beams. The obtained data were buffered in FIFO (*First In First Out*) memory (pipelines) awaiting for the positive decision of Global First Level Trigger (GFLT). In the same time a subset of data (so called trigger decision data) was analyzed by local FLT processors and the results passed to the global GFLT processor. GFLT was capable to correlate information collected from various components and delivered final decision. This level was implemented fully on hardware level using dedicated integrated circuits. The maximal rate of GFLT decisions (*Accept* signal) was about 1 kHz. After positive GFLT decision data were copied from the pipelines to the Dual Port Memory (DMP) being the second level buffer. Again, a subset of data was processed by the local SLT (Second Level Trigger) processors and passed further to the global GSLT processor. In the case of positive GSLT decision (maximal rate of about 100 Hz) data from DMP memory were transferred do the RAM memory and via the network of parallel processors (transputers) passed to the Event Builder (EVB) collecting complete data set from all subcomponents. From the Event Builder data were transferred to the Third Level Trigger (TLT) running simplifier version of reconstruction algorithms on a farm of fast workstations. At TLT events were classified according to their topology and interesting events were selected for the mass storage forming the Raw Data archive.

In the case of the BAC first level muon trigger, for each wire tower, two quantities were calculated: the sum of active chambers and the sum of active planes. This operation was performed in the 356 modules of hit-readout (hitboxes) located directly on the surface of the detector. Each hitbox was also equipped with Look-up Table Memory (LTM) allowing to implement simple pattern recognition algorithm. They selected hit patterns compatible with the passage of minimum ionizing particle (MIP). If such a muon candidate was identified in a given wire tower a muon bit `X=1` ("muon in the tower") was fired. For the purpose of the trigger system the Backing Calorimeter was divided into 13 areas, each of them containing up to 16 towers. At the area level it was possible to correlate the position (hit) readout with the energy readout and confirm the muon candidate using additional requirements. In the case of positive muon identification in the area a muon bit `b0=1` ("muon in the area") was fired. Final FLT decision delivered by BAC to the GFLT processor was a 13 bits word containing (for each HERA clock) a collection of `b0` bits coming from individual areas. On GFLT level this information was correlated with data coming from the Uranium Calorimeter (CAL) and from the Central Tracking Detector (CTD). The implementation of the BAC FLT muon trigger required the construction of additional trigger boards: The XYREC modules collecting muon bits from all 13 areas and the BMBAC (*Bits Main BAC)* responsible for passing the final BAC decision to the GFLT processor. The XYREC boards were connected to hitboxes and were also responsible for relative synchronization of muon bits coming from various calorimeter towers. The new boards manufactured using the FPGA technology were also capable to perform rich diagnostic functions including the rate measurement for all individual trigger towers. At the second trigger level (GSLT) the decisions of BAC FLT were supplemented with additional information allowing to reject non ep events coming mainly form the interaction of protons with the residual gas in the vacuum beam pipe (beam gas events) and cosmic rays induced events. At the third level of the BAC muon trigger a reconstruction algorithm were performed starting from the clustering of active anode wires and cathode towers and fitting the muon trajectories to preselected muon segments. These trajectories were subsequently matched to the CTD tracks allowing for the determination of muon momenta and with CAL MIP-like islands. The last requirement was introduced to increase the purity of muon selection. For instance it was used for the study of exclusive muon pair production.

The Backing Calorimeter and its muon trigger was running failure-free during the whole HERA-II

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phase and delivered data sample corresponding to about 200 pb^{-1} in the period of full implementation of all its three muon trigger levels. BAC was successfully competing with muon chambers designed exclusively for muon identification: at the lowest hardware levels (FLT and SLT) in the forward barrel region it was equally efficient comparing to BRMUO chambers and at third trigger level and in off-line muon reconstruction was superior to FMUON and BRMUO chambers in all areas.

Thanks to the data collected, the Backing Calorimeter was fully included to the physics analyses related to the muon production in the final state [32–35], giving the biggest contribution to the study of processes with heavy b-quarks production with their subsequent decay into muons. For example, in the analysis [32] the total cross section for the process of exclusive $\Upsilon(1S)$ vector meson production in γp interaction was measured, for the values of γp center of mass energy $60 < W < 220$ GeV, yielding: $\sigma(\gamma\text{p} \to \Upsilon(1S)\text{p}) = 235 \pm 47^{+30}_{-40}$ pb. The collected statistics of Υ mesons allowed also to determine the cross section dependence on the W variable, parameterized by $\sim W^{\delta}$ formula and to estimate the value of δ parameter $\delta = 1.2 \pm 0.8$. This is the biggest value of this parameter observed for the exclusive production of vector mesons. The increase of δ index for heavy vector mesons is related to the gluon distribution inside proton and to rapidly raising gluon density at small values of Bjorken variable x dominanting for large values of γp center of mass energy W. In the vector meson production models based on Regge theory the observed rise of δ index is described as the transition form "soft" to "hard" Pomeron ($\mathbb{P}$) exchange between the proton and the formed vector meson. The application of the Backing Calorimeter in physics analyses was also described in more details in the habilitation monograph.

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