CMS EXPERIMENT

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1. Introduction

The Compact Muon Solenoid (CMS) is a general-purpose detector designed to study physics of proton-proton collisions at center-of-mass energy of 14 TeV at full LHC luminosity up to L = 10^{34} cm^{-2} s^{-1}. The primary goals of the CMS experiment will be the Top-quark physics, search for the Standard Model Higgs bosons, as well as search for physics beyond the Standard Model (super-symmetric particles, new heavy gauge bosons, extra-dimensions …). The design of the CMS detector emphasizes the importance of precise momentum measurements of muons, electrons, and photons, resulting in excellent mass resolution needed for discovery of the new particles. Figure 1 shows general view of the CMS detector. The basic elements of this detector are:

- Superconducting solenoid
- Return iron yoke
- Inner tracker
- Crystal electromagnetic calorimeter
- Hadron calorimeter
- Muon system
- Very forward calorimeter

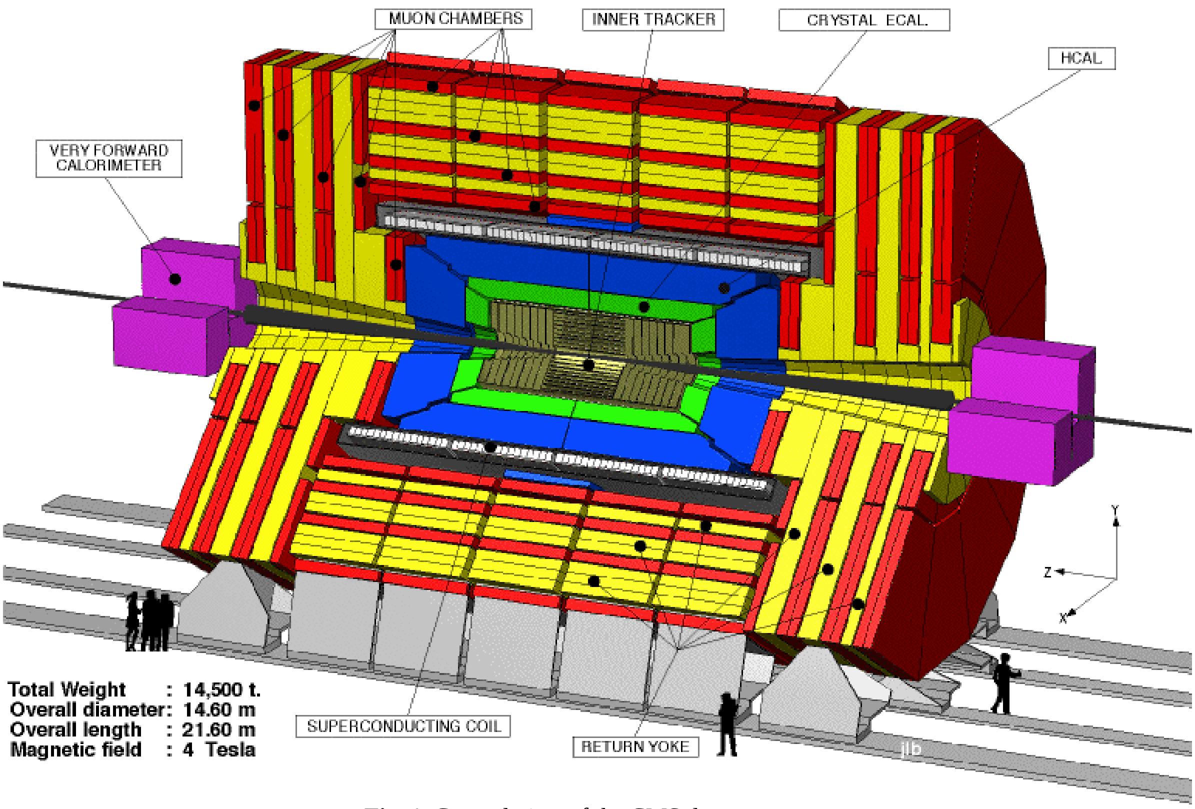


Fig. 1. General view of the CMS detector

2. Muon System of the CMS detector

The Muon System has three functions: muon identification, muon momentum measurements, and muon trigger with well defined p_t threshold from a few GeV/c to 100 GeV/c in the rapidity range up to η = 2.1. The momentum resolution $\delta p_t/p_t$ in the stand-alone mode is around 10% at p_t = 10 GeV/c and around 30% at p_t = 1 TeV/c. The global momentum resolution after matching with the Central Tracker is about 1.5% at p_t = 10 GeV/c and about 15% at p_t = 1 TeV/c. The Muon System is embedded inside the magnet return yoke. It consists of two parts – Barrel and Endcaps.

The main PNPI responsibility in the CMS project is participation in design, construction and operation of the Endcap Muon System. This work was carried out since 1994 in close cooperation with the teams from Fermilab, from University of Florida, and from some other US Universities.

In fact, development of a muon system for collider detectors began at PNPI already in 1991, when construction of the proton-proton Super Collider SSC for the energy of 20 TeV + 20 TeV was started in the USA. At that time, PNPI together with Brookhaven National Laboratory proposed the Muon System for the GEM detector, which was one of the two collider detectors to be constructed at SSC. This system was based on application of multiwire Cathode Strip Chambers (CSCs). During preparation of this project, several CSC prototypes have been constructed and tested. Also, various gas mixtures were investigated, and one of them ($Ar/CO_2/CF_4$) was recommended. It was demonstrated that such system can provide the required spatial and time resolution, and it can generate the stand-alone muon trigger. At the beginning of 1993, this project was considered by the GEM collaboration together with two other competitive projects. As the result, our CSC based project was selected for the whole GEM Muon System. Unfortunately, construction of the SSC was stopped by the USA Congress in October 1993. After that decision, several US teams organized new collaboration which proposed in February 1994 to build the Endcap Muon System for the CMS detector, similar to that designed for the GEM detector. PNPI became a member of this collaboration.

The CMS Endcap Muon System (EMU) consists of two symmetric parts (forward and backward). Each of these parts contains four Muon Stations (ME1 to ME4). The Muon Stations are composed of muon chambers placed between the iron discs of the magnet return yoke. Each of these discs has 14 meters in diameter. The station ME1 has three rings of muon chambers (ME1/1, ME1/2, ME1/3). The stations ME2 and ME3 are composed of two rings of the chambers (ME2,3/1 and ME2,3/2), while the station ME4 has only one ring of the chambers (ME4/1), the construction of the ring ME4/2 being staged due to financial limitations. The total area covered by the muon chambers is about 1000 m^2.

The muon chambers [1–4] are specially designed six-plane CSCs of trapezoidal shape as shown in Fig. 2. Cathode planes are formed by honeycomb panels with copper clad FR4 skins. Strips run radially in the endcap geometry and provide the φ-coordinate of muon hits with an accuracy of ~100 μm. Wires are stretched across the strips and, for readout purposes, are grouped in bunches from 5 to 16. They provide the radial coordinate of the muon hits with a few cm precision. In total, the EMU system comprises 540 muon chambers which contain about 2.5 million wires grouped into 210,816 anode channels. Also, there are 273,024 cathode channels.

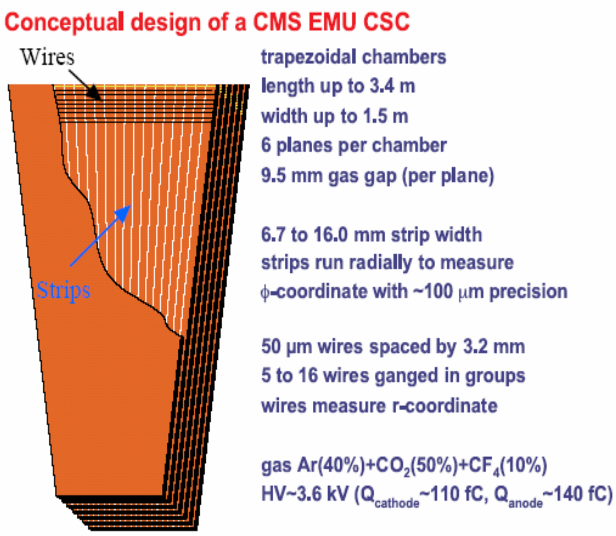


Fig. 2. Sketch view and some parameters of a CSC

3. Assembling of EMU muon chambers at PNPI

The design of the muon chambers and development of technology for the chamber production were performed with active participation of the PNPI team. The assembling and testing of the chambers was distributed between several laboratories. PNPI was responsible for assembling and tests of all muon chambers for the regions ME2/1, ME3/1, and ME4/1. In total, 120 muon chambers (40 chambers of each type) were to be produced at PNPI. Each chamber contains six sensitive planes. So, in fact, we had to build 720 one-plane chambers with total area of more than 1400 m^2 and with total number of the anode wires about half a million.

To accomplish this task, a special facility (muon chamber factory) was prepared at PNPI. This facility occupied about 500 m^2 area, including some clean rooms. It was equipped with special tooling developed jointly by PNPI and US_CMS specialists. In particular, this equipment included a wire-winding machine, a wire pitch and tension measuring machine, special gluing tables, assembling tables, a setup for cleaning the anode wires with ionized nitrogen gas, a gas leak test stand, a γ-rays test stand, a cosmic rays test stand, and some other tooling. This equipment allowed to organize the chamber assembling under well controlled conditions with the necessary production rate of one six-plane chamber per week. The developed chamber assembling technology was approved by the EMU collaboration after the Production Readiness Review which was held at PNPI in June 2001.

The mass production of the muon chambers at PNPI was started in October 2001. The US_CMS collaboration provided prefabricated parts of the muon chambers (honeycomb panels, anode and cathode bars, *etc*.) and most of the materials needed for assembling the chambers. The metallic chamber frames were produced at PNPI. The assembling procedure was controlled at each step: flatness of the honeycomb panels, height of the gas gaps, wire tension, wire pitch, gas tightness. The assembled chambers were trained under high voltage with simultaneous measurement of the dark current. It was required that the dark current should not exceed 100 nA in each plane at the nominal high voltage HV = 3.6 kV. In case of problems, the chambers could be disassembled for additional cleaning. The gas gain uniformity was controlled on the γ-rays test stand by measuring current induced by a collimated γ-source movable over the chamber surface (Fig. 3). The variations of the gas gain should not exceed ± 50%. All details of the assembling procedure for each chamber together with the results of the control measurements were collected in special folders (Fig. 4) which will accompany the chamber in its further life. Also, this information was placed in a special data base reachable for the EMU collaboration *via* Internet.

Fig. 3. Muon chamber on the γ-rays test stand

Fig. 4. Muon chamber ready for installation of the on-chamber electronics

The on-chamber electronics was installed on the chambers which passed the above mentioned tests (Fig. 5). After that, the chambers were tested on the cosmic rays tests stand (Fig. 6).

Fig 5. Installation of the on-chamber electronics

Fig. 6. Final tests of the muon chambers on the cosmic ray test stand

The on-chamber electronics included anode and cathode FE boards and also logical boards ALCT and CLCT which allowed on-line reconstruction of the tracks using hits from the six layers of the chamber. The final test program included 36 various tests with pulse generator and with cosmic muons. Figure 7 shows one of the cosmic rays events detected by the muon chamber. The measured amplitudes of the signals in the cathode strips in all six layers are shown by red bars, while the blue bars represent the hits in the anode wire groups. After final tests, the chambers were stored in a special room for one month training under nominal high voltage. Then the chambers were prepared for transportation to CERN – see Figs. 8–9. By the end of 2006, all 120 muon chambers produced at PNPI were safely delivered to CERN.

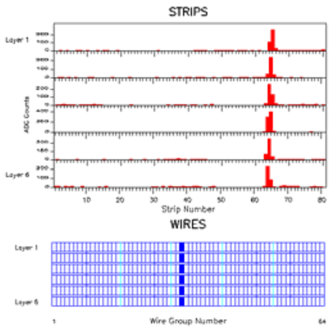


Fig. 7. Display of a cosmic ray event

Fig. 8. The PNPI team in front of the last muon chambers ready for transportation to CERN

Fig. 9. The track with twenty muon chambers prepared to move for CERN

4. Testing of EMU muon chambers at CERN and installation in the CMS detector

Fig. 10. High-level visitors at the EMU test stand.
CERN General Director R. Aymar, Minister of Science and Education of the Russian Federation A. Fursenko and others

All muon chambers produced at PNPI, FNAL (USA), and IHEP (China) were transported to CERN where they have been tested again on a special test stand, following the same test program as in the production centers. The PNPI team played the leading role in these tests. In total, about 500 chambers have been tested. All chambers showed very good performance: high detection efficiency with a large HV plateau, low noise. During these tests, some minor problems in the electronics have been detected and fixed.

Some of the muon chambers were tested on the γ-radiation facility GIF at CERN to study their aging properties. It was demonstrated that the chamber performance is not deteriorated noticeably up to the integrated radiation dose corresponding about 30 years operation of the EMU system.

Figure 10 illustrates attendance of the EMU test stand by high-level visitors.

The assembling of the CMS detector was performed in two stages. First, all the subsystems were installed in the on-surface hall. Figure 11 shows how one of the muon chambers is lifted by a special transporting system for installation on the iron disc of the magnet return yoke. One can see also the chambers already fixed at the disc. All the infrastructure and electronics are installed at the same time. This allowed to perform some tests of the EMU system already in this phase of installation. In particular, important tests were carried out in 2006 with cosmic rays using a part of the assembled EMU system comprising muon chambers in all muon stations. In the second phase of installation, the separate pieces of the CMS detector are lowered down in the underground hall for the final assembling. Figure 12 demonstrates the process of lowering of one of the iron discs with the muon chambers and all related infrastructure. Note that the weight of the disc exceeds 1000 tons.

The PNPI team takes an active part in installation of the EMU system. The full installation of the CMS detector should be finished at the beginning of 2008.

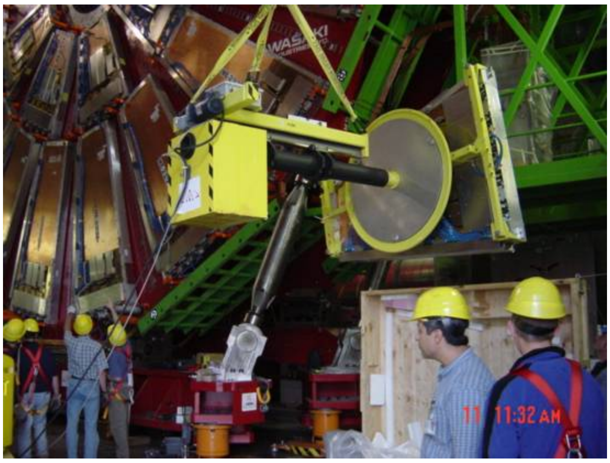


Fig. 11. Installation of a muon chamber on the iron disc of the magnet return yoke

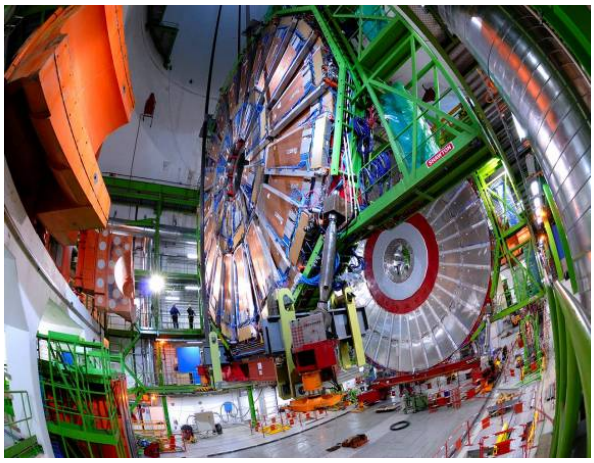


Fig. 12. The lowering down of one iron disc with muon chambers in the underground hall

5. Multi-channel high voltage supplier for the EMU system

The EMU system comprises 468 six-plane muon chambers. In addition, the HV line in each layer is divided in several sections (5 sections in chambers ME2,3/2 and 3 sections in all other chambers). So in total there are more than 9000 sections with independent HV lines. This increases essentially the redundancy of the system as, in case of problems, only one section will be switched off that should not deteriorate noticeably performance of the whole EMU system. Such design dictated development of a special multi-channel HV system which could satisfy the requirements of the CMS experiment. This problem was solved by joint efforts of specialists from PNPI and University of Florida. The block diagram of a quarter of the designed HV system is presented in Fig. 13, the stand for tests of EMU high voltage system at PNPI is shown in Fig. 14. The high voltage from the Primary HV power supplier is distributed for about 2400 HV lines with independent regulation of the voltage in each line. Also, the current in each line is under control with a possibility to switch off any line by burning off a fuse, if necessary. The HV distribution is done in two stages. First, it is distributed by nine Master Boards into 72 HV lines with HV regulation from 0 to 4 kV. These lines go *via* ~100 meter long cables to 72 Remote Distribution Boards. Each such board has 30 or 36 outputs going directly to the muon chambers. The Board 30 feeds one big chamber ME2,3/2, the Board 36 feeds two smaller chambers. The Remote Distribution boards can regulate the voltage in each output channel by 1 kV down from HV_{max} .The maximal current in each channel of the HV system is 100 μA.

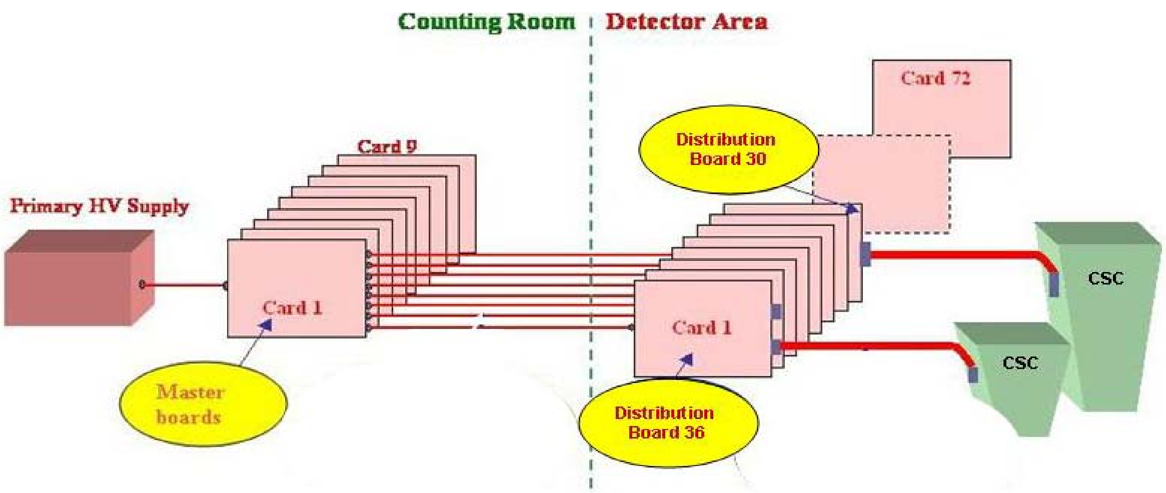


Fig. 13. Block diagram of a quarter of EMU HV system

The HV system is controlled by computors *via* the Host Cards (not shown in Fig. 13). Each Host Card controles up to 16 Distribution or Master boards. An important requirement is radiation hardness of the Remote Distribution boards as they are placed close to the muon chambers. The tests of the designed boards with gamma and neutron radiation showed that they can operate without problems in the expected radiation environment. The production of the designed HV system was accomplished by the PNPI-UF collaboration. By mid of 2006, all modules for the 9000-channel HV system (plus spare modules for 2500 HV channels) were produced, tested, and delivered to CERN for installation.

Fig. 14. Tests of EMU high voltage system at PNPI

6. Track-finding processor for the EMU system

The Track Finding Processor (TFP) is a basic element of the EMU trigger system [5–6]. The purpose of the TFP is to link track segments from the individual muon stations into complete tracks, to measure the transfer momentum from the sagitta induced by the magnetic bending, and to report the number and quality of the tracks to the Level-1 global trigger. The TFP was designed by PNPI engineers in cooperation with the University of Florida. It is implemented as 12 processors working in parallel. Each of them should identify up to three best muons in the corresponding 60° azimuthal sectors. The block diagram of the TFP is shown in Fig. 15, the demonstration of Track-Finding Processor is presented in Fig. 16. The design of the TFP is based on the most advanced Field Programmable Gate Array (FPGA) chips, each of them containing more than one million logical elements.

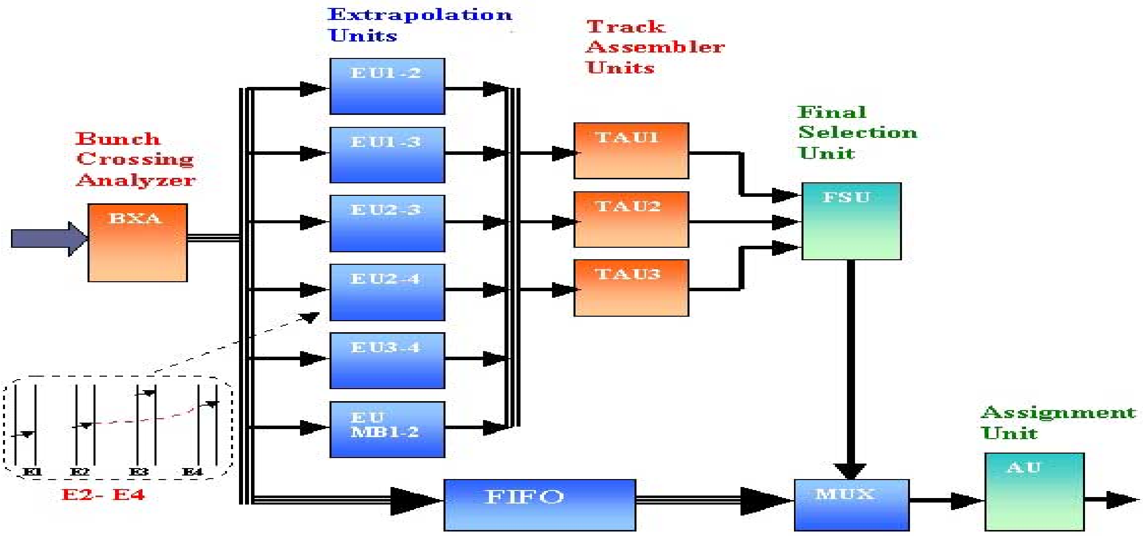


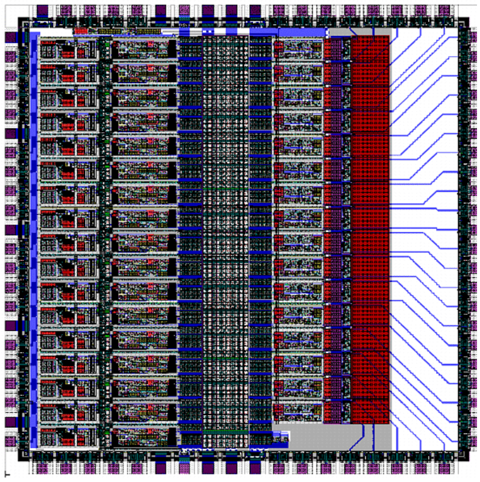
Fig. 15. Block diagram of Track-Finding Processor

The first TFP prototype was fabricated in 2000 and successfully tested in 2000–2001. This was quite a big system containing forty eight 9U VME modules . The processing time of this TFP was 375 ns. The experience obtained from testing of this prototype and also appearance on market of more powerful FPGA chips allowed to design a new, more advanced TFP. The total volume of this TFP was decreased by a factor of 4 (twelve 9U VME modules), and the processing time was reduced down to 175 ns. The TFP was fabricated in the US industry, while testing and commissioning of this system was done by PNPI engineers in cooperation with specialists from University of Florida. The combined tests of the EMU trigger system performed in the proton beam (2004) and with cosmic rays (2006) showed very good performance of the constructed Track-Finding Processor.

Fig. 16. Demonstration of Track-Finding Processor

7. Anode front-end electronics

The PNPI engineers in cooperation with Carnegie-Mellon University designed the anode front-end electronics for the EMU muon chambers [7]. For this purpose two integrated circuit chips were designed. One of them (CMP16 – see Fig. 17) included 16-channel amplifier-shaper-discriminator. The other one (DEL16) provided a programmable delay line for each channel which allows time alignment of the signals with a delay step of 2 ns. On the basis of the CMP16 chip, a 16-channel Anode FE (AD16) board was designed. The designed board passed through various reliability and radiation tests. The fabrication of the CMP16 and DEL16 chips, as well as the AD16 boards was carried out in the US industry. The tests of the produced chips (22,000 chips) and boards (12,000 boards) were performed by the PNPI specialists. These tests showed that the major part of the produced electronics was of good quality. By the end of 2002 all the boards were tested and provided for installation onto the muon chambers.



Fig, 17. CMP16 (Bondar's chip) layout

8. Alignment of the muon chambers in the EMU system

The 468 EMU muon chambers are fixed on the magnet return discs covering the area of 1000 m^2. Their geometry position in the CMS absolute coordinate system should be known with 100 micron precision in the azimuthal plane and with 1mm precision in the Z-direction. This task becomes even more complicated because of significant deformation of the iron discs in the magnetic field. Therefore, permanent control for positions of the muon chambers is needed. For these purposes, a complicated system was developed comprising several hundreds of position-sensitive detectors irradiated by the laser beams. This work was done by engineers from the Wisonsin University with active participation of PNPI specialists [8]. The global tests of this alignment system were carried out in 2006 with the half of the EMU system assembled in the on-surface hall. These tests showed very satisfactory results. The second half of the EMU system will be equipped with alignment devices in 2007.

9. Photodetectors for CMS Endcap Electromagnetic Calorimeter

The CMS Electromagnetic Calorimeter (ECAL) is based on lead tungsten crystals ($PbWO_4$). These crystals offer excellent energy resolution due to high density (8.28 g/cm^3), a small Moliere radius (2.0 cm), and a short radiation length (0.89 cm). Also, they provide a quite fast (~10 ns) output signal, and they can operate in high radiation environment. ECAL consists of the Barrel part ($|\eta| < 1.48$) and two Endcaps ($1.48 < |\eta| < 3.0$) with 61200 and 21528 crystals, respectively. The total volume of the crystals amounts to 8.14 m^3 (67.4 tons) in the Barrel and 3.04 m^3 (25.2 tons) in the Endcaps.

The light from the crystals should be detected with radiation hard photodetectors, especially in the Endcaps where the radiation level is much higher than in the Barrel. After extensive studies, the preference was given to the Silicon Avalanche Photodetectors (APD) in the Barrel and to the more radiation hard Vacuum Phototriods (VPT) in the Endcaps. PNPI in cooperation with the Research Institute Electron (RIE, St.-Petersburg) carried out studies of various kinds of VPTs produced at RIE [9–10]. These studies resulted in construction of a VPT (FEU-188) which could satisfy the requirements of the CMS experiment. This VPT has a flat geometry with a photocathode (25.5 mm in diameter) followed by a mesh and by a solid dynode. The VPT provides the required gain of 10–12, and (what is most important) this gain does not decrease in the presence of magnetic field up to B = 4 T. Another advantage of the developed VPT is low sensitivity to variations of the anode voltage.

As a first step, a sample of 500 VPTs was produced at RIE. The gamma radiation tests of these VPTs showed that the gain degrades only by ~7% after the radiation doze of 20 kGy (the doze expected for 10 LHC years). Also, VPTs were tested with a real ECAL prototype showing very good performance. Based on these results, the CMS collaboration decided to equip the ECAL Endcaps with the FEU-188 and has signed a contract with RIE for production of 16000 VPTs. The production of the VPTs was completed by mid of 2006, and they were delivered to CERN. The new tests demonstrated high quality of the produced VPTs. As the result, the CMS collaboration has taken decision to reward the Research Institute Electron by a special CMS Gold Medal 2007 for outstanding contribution of the industry to construction of the CMS detector – see Fig. 18.

Fig. 18. The CMS Gold Medal-2007 to Research Institute “Electron” for outstanding contribution to construction of the CMS detector

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