Summer Undergraduate Research Exchange Report
Cathode Strip Chambers Production for CMS Endcaps

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Abstract

The author had participated in the Summer Undergraduate Research Exchange (SURE). He spent 8 weeks in CERN working in Building 904 of CERN Prevessvin Site, with a hardware group supervised by Dr. Armando Lanaro. The Group the author worked with is upgrading the Endcap Muon system of Compact Muon Solenoid (CMS). The Endcap Muon system is designed to detect muons at high absolute pseudorapidity (η). The aim of the group is to manufacture 72 additional Cathode Strip Chambers (CSC) in ME4/2 site, to fully equip the YE3 endcap yoke disk. During the author's stay, the group planned to manufacture 3 CSC prototypes before beginning the mass production of CSCs.

1 Introduction

The Compact Muon Solenoid (CMS) is a general purpose particle detector installed in one of the collision sites in the Large Hadron Collider (LHC). The muon system is located at the outer layer of the CMS encompassing the whole solenoid, as shown in Figure 1. Muon detection is an essential part of the LHC

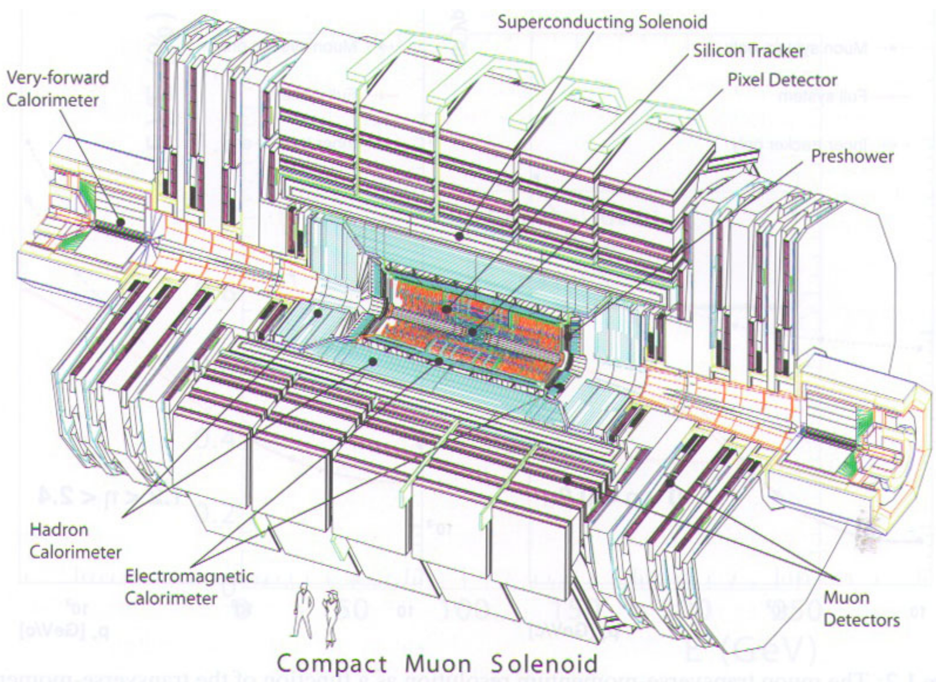


Figure 1: A perspective view of the Compact Muon Solenoid [1, p. 3].

experiments, as muon signatures are comparatively recognisable in the high background environment in LHC with full luminosity. Also, a lot of interesting processes have muon final states. This includes the predicted Standard Model Higgs boson decay

$$H \longrightarrow ZZ/ZZ^* \longrightarrow 4l$$

which is a 4 leptons decay mode. In the case all 4 leptons are muons, it can be easily identified by the muon system. Therefore, the muon system can provide the proof or disproof of various interesting processes. A good muon system in CMS is of great importance.

The factory Building 904 was set up to produce 72 CSCs for ME4/2 sites (See Figure 2). In its original design, the fourth endcap muon stations (ME4) is fully occupied with CSCs, which are mounted on the third endcap yoke disks (YE3). However, the early construction only finished the ME4 CSCs in the inner rings (ME4/1). With the LHC luminosity (L) upgrade in the year 2014 and after ($L > 2.3 \times 10^{34}\, cm^{-2} sec^{-1}$). An Endcap Muon system upgrade would become essential. One of the items of the upgrade is to install CSCs onto ME4/2. This would provide a more efficient triggering at high luminosities thanks to the increased redundancy of the system.

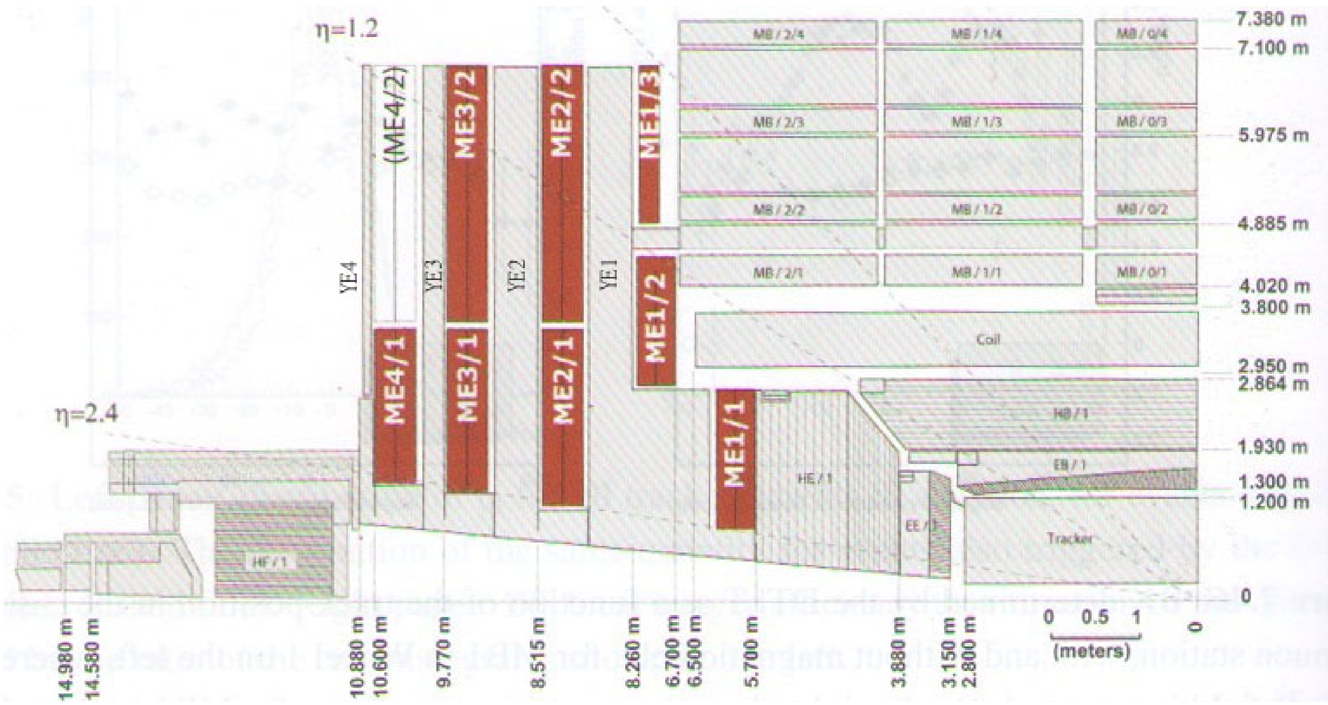


Figure 2: Quarter-view of the CMS detector showing the labeling of the subsystems [1, p. 198].

2 Muon System Design

2.1 Endcap Muon System

The CMS Muon system of contains Cathode Stripe Chambers (CSC), Drift Tubes (DT) and Resistive Plate Chambers (RPC) as subsystems, which work complimentarily. CSCs are responsible for precision muon measurement and muon tiggering in CMS. To fit in the cylindrical shape of the CMS, trapezoidal CSCs are located on the endcaps, which identify muons at $0.9 < |\eta| < 2.4$. Pseudorapidity (η) is defined as

$$\eta = -ln[tan(\theta/2)]$$

where θ is the angle between the particle trajectory and the beam. $\theta = 0^o$ and $\theta = 180^o$ correspond to the direction of the particle beam. The Endcap Muon system consists of 468 CSCs before the upgrade.

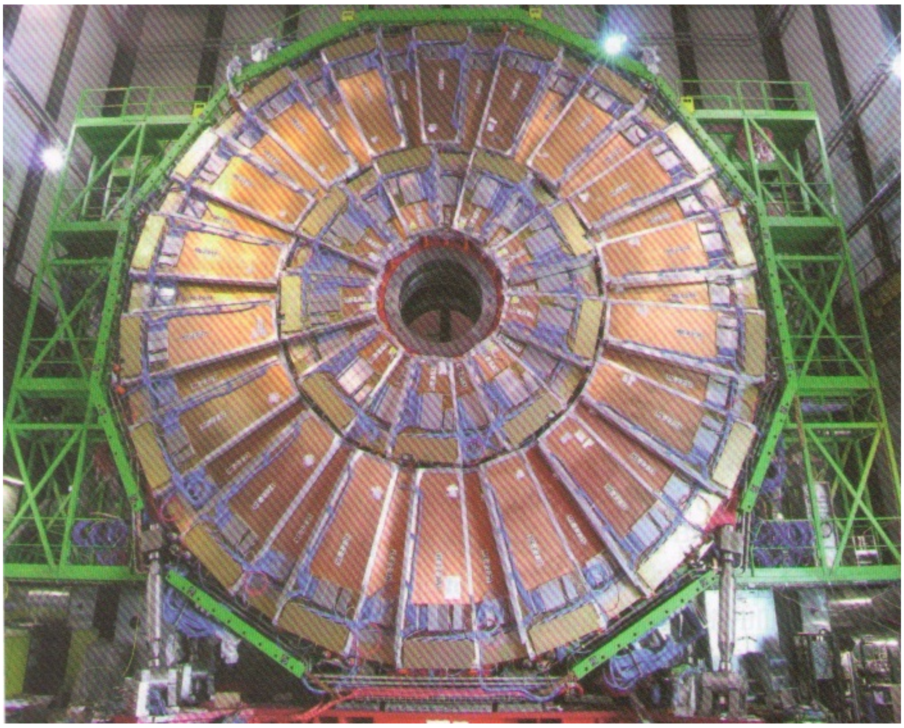


Figure 3: A photo of Muon Endcap 2 (ME2) [1, p. 198].

The CSCs are installed in an overlapping manner such that each muon traversing the endcaps must pass through 3 or 4 CSCs before escaping the system.

The ME4/2, which is the outer ring of ME4, consists of 72 CSCs. It covers the region of $1.2 < |\eta| < 1.8$. With the completion of ME4/2, the endcap will be fully covered by a total of 6 planes of CSCs. The time and position resolutions depend heavily on the 6-plane coincidence. It is important to cover all angles at the endcap with 6 planes of CSCs such that the events at all pseudorapidity will be of equal high resolutions. Moreover, the increase of muon system redundancy can greatly improve the muon triggering. For example, with ME4/2, the CSC trigger rate is 5 kHz at 20 GeV/c threshold. Without ME4/2 at the same threshold, the trigger rate is 13 kHz, which is substantially higher. In addition, the rejection of neutron hits is more effective with the 6 planes of CSCs [3]. These factors combined ME4/2 can significantly booster the effectiveness of muon triggering at high pseudorapidity.

2.2 Cathode Strip Chambers

CSCs are designed to measure muon position with great precision of millimeters order. They are designed to be durable under high radioactive, low maintainance and low control environment for at least 10 years. They can operate at high rates and in strong, non-uniform magnetic field.

CSCs at endcap are trapezoidal chambers made of 3 anode panels and 4 cathode panels, which are put together in alternating manner (panels 1, 3, 5, 7 are cathode panels and panels 2, 4, 6 are anode panels). The CSCs discussed in this report are in ME4/2, which have the same mechanical design with those in ME2/2 and ME3/2. They are the largest chambers ($3.4 \times 1.5\,m^2$ in size with 3.4 m being the length of the trapezoid and 1.5 m being the base). Each chamber spans 10^o azimuthal angle (ϕ).

Figure 4 shows the two key features of CSC panels. All panels except the bottom cathode panel have strips pattern. Each of the six panels has 80 strips milled on one side of it in radial direction, each separated by 8.4 mm at the narrow end of the trapezoidal panel and 16.0 mm at the wide end. Each of the conducting areas between the strips form its individual channel. On each side of the anode panels, about 1000 thin Gold-Tungsten wires of $50\,\mu m$ diameter are wound perpendicular to the strips pattern, with neighbouring wires separation (pitch) $3.2\,mm \pm 150\,\mu m$. About every 16 wires are grouped together to

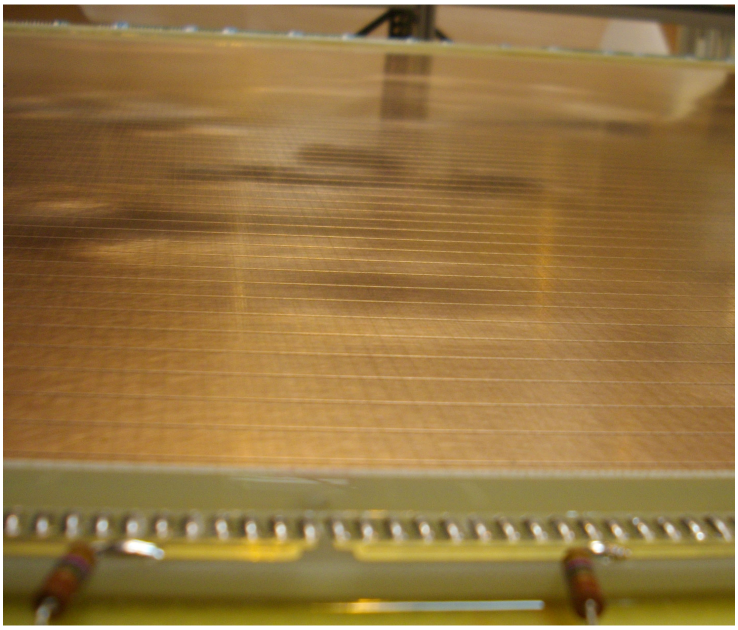


Figure 4: Close-up on one of the slanted edges of the strip side of an anode panel. The horizontal lines on the panel are strips running in radial direction. The thin vertical lines are AuW wires running perpendicular to the strips. They are 4.75mm above the panel. The bar at the front is wire fixation bar where the wires are soldered on.

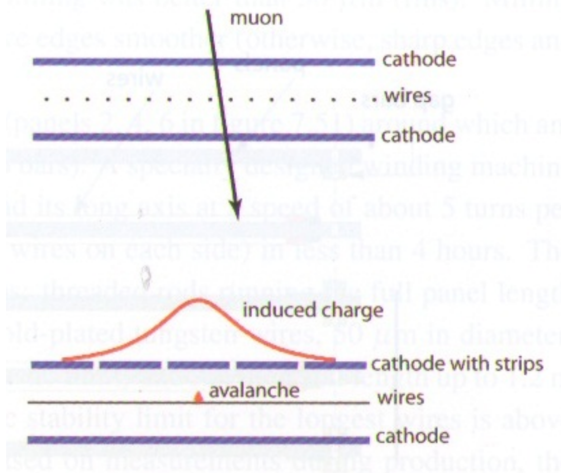


Figure 5: Mechanism of CSC in detecting incoming muon [1, p. 199]. A muon causes an electron avalanche between two panels. The ionization charges are with a Gaussian profile. Positive charges are picked up by the wires and electric signal is generated.

form a read-out channel spanning across a width of 5 cm on the panels. Also, the 1000 wires are divided into 5 high voltage (HV) sections. Thick Beryllium-Copper wires of 200 μm diameter must be placed on the edges of each high voltage section in order to remove the edge effect of the electrostatic field. All the wires are soldered onto wire fixation bars glued on both slanted sides of the anode panel. The wires are maintained 4.75 mm above the panel, which is half the height of the gas gap.

Between each panels is a gas gap of 9.5 mm height defined by gap bars glued on the perimeters of the cathode panels. The gas gaps form 6 gas compartments of combined volume $0.2\,m^3$ inside a chamber, which are to be filled with a gas mixture of $40\%\,Ar + 50\%\,CO_2 + 10\%\,CF_4$ at atmospheric pressure. CO_2 is a non-flammable quencher and CF_4 is to prevent polymerisation on wires.

During operation, the wires are charged to 3.6 kV. When a muon traverses a CSC, ionization charges are produced in the gas gaps. They are accelerated by the potential difference and are picked up by the wires and the panels. Since the wires and strips are perpendicular to each other, the 2D position of the signal on the panel can be found out.

The CSCs are a very effective muon track finder with 99% efficiency per chamber for finding muon track stub by first-level trigger. The individual chamber is of $\sim$ 2 mm $r - \phi$ position resolution and $\sim 150\,\mu m$ off-line spatial resolution. The anode signals from a single plane has an RMS time distribution of 11 ns. While all of the 6-plane CSCs in the muon stations are used, the spatial and time resolutions can be improved. The spatial resolution can be boosted up to 80 μm. The signal's time spread (σ) will also be reduced to less than 5 ns, which improves the bunch-tagging efficiency to 98% - 99%.

3 Cathode Strip Chamber Production

3.1 Production Line

The production line for CSCs is located in bâtiment 904 (B904), site de Prevessin in CERN. The production team led by Armando Lanaro aimed to produce CSCs for ME4/2 sites to fully equip yolk disk YE3. During the summer 2011, the team started the production of the first few CSC prototypes. A total of 21 panels, 12 cathode panels and 9 anode panels, were received by the team, given CSC consists of 4 cathodes and 3 anodes. If the prototypes function properly, they will be installed onto ME4/2 site along with the CSCs that are mass-produced after that summer.

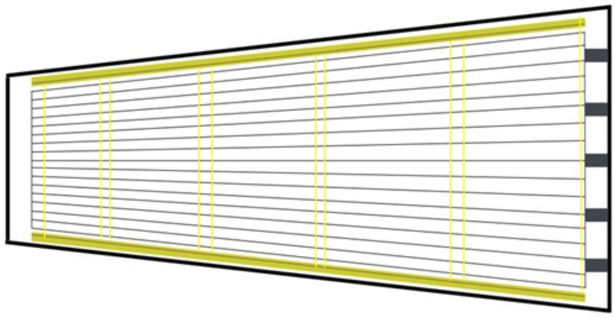


Figure 6: A diagram of the strip side of an anode panel. This type of anode panel will be used in the CSCs in ME4/2. The thin black lines running horizontally are strips. The few golden lines running vertically indicates the thick wires.

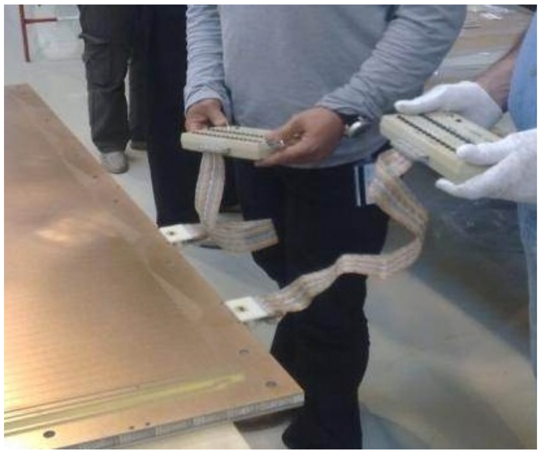


Figure 7: An anode panel is examined for whether different detection sections separated by the strips are well-insulated from one another.

When the anode and cathode panels are shipped to B904, they are firstly inspected visually for damages and defects. Also, the conductivities between different detection areas sectored by the strips are tested (in Figure 7). This can reveal whether the detection areas are separated properly. If they are in good condition, the panels will be cleaned by pure ethanol thoroughly and be put onto the production line.

Components are glued onto the panels in gluing station. Epoxies are used for gluing. For anode panels, wire fixation bars of 4.75 mm thickness are glued on both the slanted edges, on both strip side and non-strip side of the panels. For cathode panels, gap bars are glued along the perimeters of the panels. Pressure had to be applied to the glued bars overnight to ensure solid gluing. The gap bars provide insulation, define the gas volume and determine the nominal separation between cathode and anode panels. The gap bars also define the air-tight envelope in which gas mixture used in CSC is trapped. On the inner edges of the gap bars, thin insulation strips are glued to provide extra insulation. For both panels, O-rings are glued into the holes of the panels designed for the circulation of CSC gas mixture.

After that, cathode panels are put onto storage carts while anode panels are to be prepared for wire winding process. The anode panels are cleaned again. This time, stains and oxides layer are throroughly brushed off from the panel surfaces. Two cones for fixing the thin wires position during winding, one straight and one threaded, are installed onto the slant edges of the panels. The cones are calibrated with fish wires in order to align the indentations of the cones to the fixation bars. After that, the cones are tightened by bolts and nuts.

2 thick BeCu wires of 200 μm diameter are installed on the 2 edges of the 5 HV sections of each side of the panels. That is totally 20 thick wires are installed on one anode panels. The thick wires are hand soldered onto the fixation bar. Weights are used to maintain the thick wire at nominal tension

Figure 8: A gap bar is being placed and glued onto a cathode panel.

Figure 9: Epoxy is applied through a syring to the position where insulation strip is to be placed.

500 $grams \pm 10\,\%$. A portable tension machine is used to check that the thick wires are properly tensioned.

The thin wire winding process takes place in clean room 1. Thin AuW wires of $50\,\mu m$ diameter are wound onto the anodes panels by an automated winding machine. The tension of the thin wires are set to be $250\,grams \pm 10\,\%$ and wire separations (pitches) to be $3.2\,mm \pm 150\,\mu m$. The wound wires are fixed in the indentations of the previously aligned cones. It takes about 3.5 hours to completely wind the ~ 1000 wires on each side. After winding, a mylar strip is glued onto each side with wire fixation bars. Upon placing mylar strip, the wire positions have to be manually adjusted before the epoxy solidify in order to keep the wires in the range of acceptable pitches. Then, mylar sheets are placed onto the detection area to protect the wires and the panel from contamination during soldering. On the top side of the glued mylar strips is a sticky layer which can fix the mylar sheets. After that, the anode panels are put into an automatic soldering machine. The soldering machine solders all ~ 4000 joints between the thin wires and fixation bars.

Figure 10: An operating automatic wire winding machine.

Figure 11: An operating automatic soldering machine.

(a) Front View (b) Side View

Figure 12: The optical and frequency generator device with an anode panel being tested.

After soldering, the anode panel is moved to hand soldering area outside the clean room. Electronic components for cathode panels and anode panels are hand soldered onto where they belong. Resistors, capacitors, connectors and ground strips are soldered onto the panels. Thin wires in non-detection areas have to be cut and detached from the cones before hand soldering takes place on anode panels. The thin wires are connected to the anode panels by resistor-capacitor circuits. Through 1 nF capacitors, signals from thin wires are read out on one side and HV are distributed on the other side. Cones are removed from anode panels and protective mylar sheets are removed after this stage.

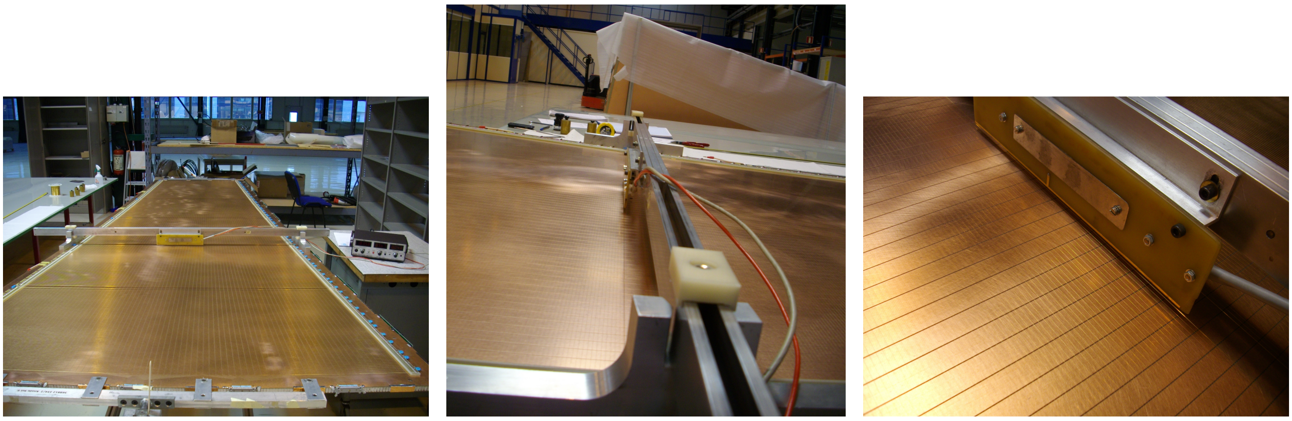
Anode panels are brought into clean room 2 for final mechanical and electrical tests before chamber assembly. Panels are cleaned with high pressure, high flow de-ionized air blade. The anode panel mechanical test consists of measuring the wire pitch and tension to see if they meet the nominal values. For this measurements an optical and frequency generator device are used. The device has a digital camera. It is programmed to measure and record the wire pitches. A frequency generator on the device can induce vibration on individual wires. By measuring the fundamental frequency of each wires, the tensions can be found since the linear mass and lengths of the wires are known accurately. Following this test, the panels are electrically tested by measuring residual currents at operating HV. The test also looks for corona discharges. 3 anode and 4 cathode panels are assembled and sealed into a Cathode Strip Chamber in clean room 2. The final test consists of operating the CSC with a neutral gas (Ar) and HV to test for leakages and electrical discharges.

The validated CSC are transported into the long term test area where they undergo a $\sim$ 2 months HV (3.6 - 3.8 kV) stability and leakage test. For this purpose, the chamber is filled with the operating gas mixture (40% Ar, 50% CO_2 and 10% CF_4). After the 2-months test all electronics components are integrated on the chamber, that is: readout and trigger boards, power and control boards and all the cable network. Then, a test of the fully integrated chamber and electronics is performed using injected test pulses and cosmic rays. This final validation of the operation of the fully assembled CSC lasts typically 2-3 days. After this test, the CSC is truly completed.

3.2 Author's Contribution

The author had participated most of the production steps from unpacking of the panels to hand soldering of electronic components.

At the gluing area, the author was a general assistant for most of the processes. The work included gathering equipment and parts, cleaning panels and parts, preparing for gluing, installing glued parts,



(a) Front View (b) Side View (c) Close-up

Figure 13: The views of the portable tension machine, focusing on the high voltage detection arm.

transferring panels, etc.

The area the author positioned for the longest time is the thick wire soldering. Since there is a traveller following each panel for each procedure, each production step had to follow exactly the travellers and each measured values had to be recorded either on the travellers or in a logbook. And each finished step has to be ticked and each page has to be signed and dated by the responsible technician. This standard procedure is the same for thick wire soldering.

The author started by removing the oxide layers and dirt from the detection area of the anode panel. Then the cones were installed. The cones were aligned to the wire fixation bar by a fish wire. The distances of misalignment were measured and recorded in the traveller. After alignment, the cones were tightened onto the anode panels. Thick wires were cleaned by ethanol and mounted onto the panels with tension-fixing weights on both end of the wires. With the help of a pulley, the thick wires were soldered onto the wire fixation bars with good tensioning and positioning. In addition, the solder on the joints had to be clean, shiny and smooth to the touch.

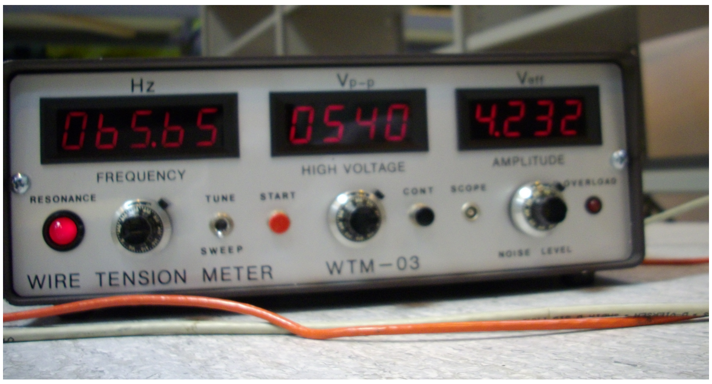


Figure 14: The reading of the portable tension machine. Left: Circuit driving frequency. Middle: Input voltage. Right: Wire vibration amplitude. Bottom left red light bulb indicates whether a resonance occurs. In the photo, a resonance was happening.

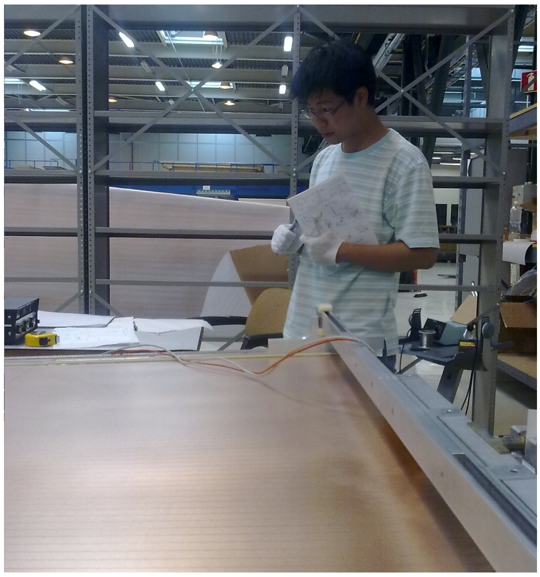


Figure 15: The author was recording the frequency reading while maintaining a safe distance from the high voltage part of the machine.

The tension of each thick wire had to be measured and recorded in the logbook. If any wire had an undertension exceeding the acceptable range, that particular wire had to be removed and a new wire resoldered. A portable tension machine was used for thick wire tension measurement. The machine produces an oscillating electric field to induce vibration on the wire being tested. By tuning the frequency of the electric field, resonance between the circuit and the wire can be produced. The machine can tell the resonance frequency by measuring the changing capacitance between the wire and the machine. The resonance frequency is at the time the fundamental frequency of the wire, thus the tension of the thick wire can be calculated from the frequency using the equation below,

$$Wire\ Tension = \mu \times (2Lf_0)^2$$

where f_0 is the fundamental frequency of the wire measured by the machine. L is the length of the wire which can be directly measured with great accuracy. And μ is the linear density of the wire which is indirectly stated on the spool of the wire ($\mu_{AuW} = 3.792 \times 10^{-5} kg/m$ and $\mu_{BeCu} = 2.608 \times 10^{-4} kg/m$ [4]).

The author participated on wire winding in clean lab 1. Although the winding machine was automatic, it had to be constantly monitored if it was working properly. Before winding begin, the machine had to be checked if the spool arm performed each step at correct distance as the step of the spool arm determined the wire pitches. A correct step was $\sim$ 126 mils corresponding to 3.2 mm pitch. Also, a few procedures, such as fastening the wires with tape and placing solder on the wire, had to be performed before winding began. During winding, the machine wound the panels using a single thread of wires from a spool. The process had to be monitored to prevent any skipping or doubling winding. At the end of winding, steps similar to those at the beginning of winding had to be performed.

Mylar strips placing, mylar sheets placing, non-detection area thin wires removal and electronic parts soldering was also carried out by the author. Although the process was conceptually simple, each step had to be performed with great care as very delicate thin wires and mysophobic detection areas were involved.

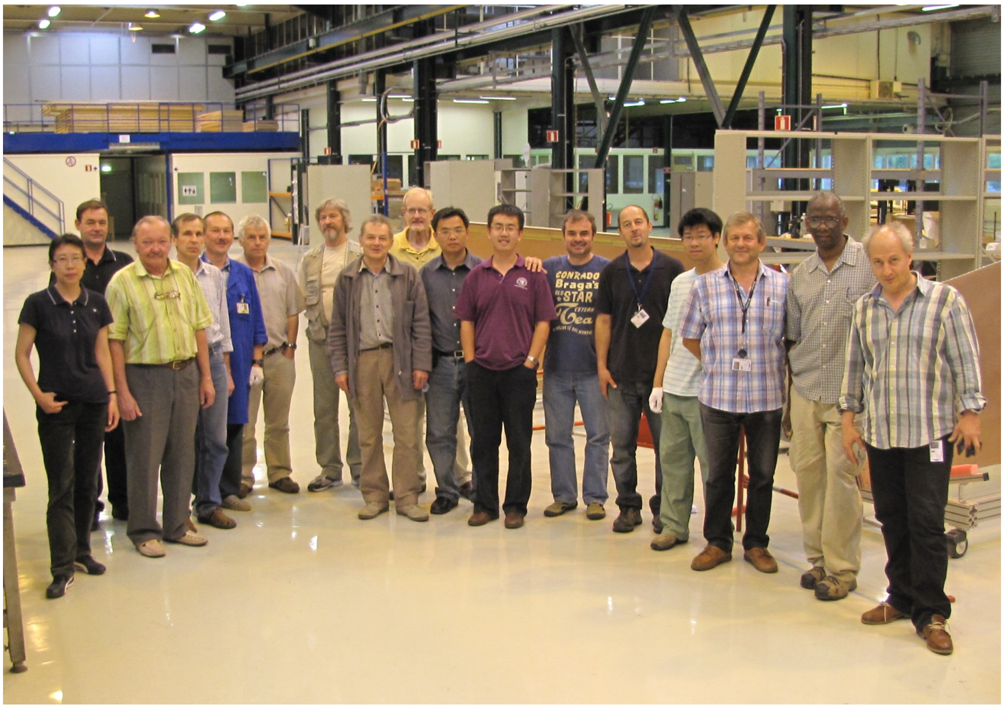


Figure 16: The B904 team.

4 Conclusion

During the period of author's stay, the B904 team received 12 cathode panels and 9 anode panels. 8 out of 9 anode panels had begun their manufacture process. The 9^{th} panel had been rejected due to panel's over-thickness. 8 cathode panels and 8 anode panels had gone through all the construction procedure. 5 anode panels had been tested for pitch and wire tension, which all passed the tests. 3 anode panels had passed HV testing, with the 4^{th} failed at the threshold current requirement [4]. The CSC manufacture process will continue in September 2011 after the team's holiday, the time well after the author finished the research exchange.

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