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The Compact Muon Solenoid Experiment

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Technical Design Report

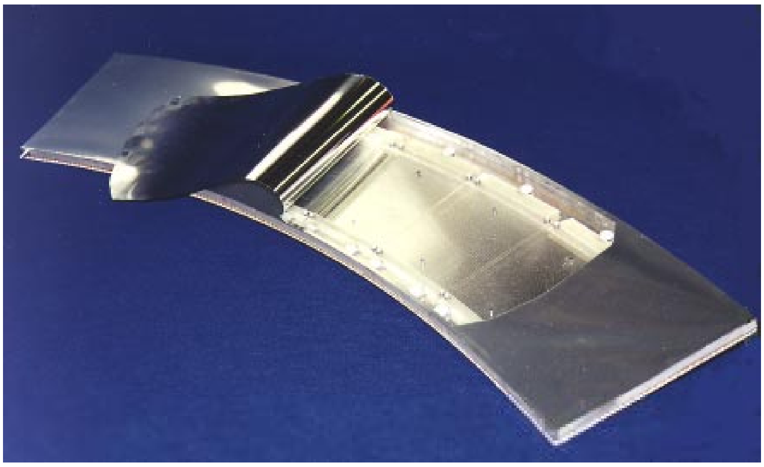
A possible approach for the construction of the CMS Forward-Backward MSGC Tracker

Abstract

A possible way of constructing,running and maintaining the forward-backward MSGC tracker of CMS is described in this note. Prototype results validating features specific to this design are also given.

Technical Design Report

A possible approach for the construction of the CMS Forward-Backward MSGC Tracker



O. Bouhali, S. Claes, J. Nelissen, J. Stefanescu, F. Udo, C. Vander Velde, W. Van Doninck, P. Van Laer, L. Van lancker, V. Zhukov(1)*
Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium

K. Bernier, G. Grégoire
Université Catholique de Louvain, Louvain-la-Neuve, Belgium

T. Beckers
Universitaire Instelling Antwerpen, Wilrijk, Belgium

I. Boulogne, E. Daubie
Université de Mons-Hainaut, Mons, Belgium

A.M. Bergdolt, J.M. Brom, J. Coffin, H. Eberlé, R. Fang, J.C. Fontaine, W. Geist, U. Guerlach, A. Lounis, V. Mack, A. Pallarès, P. Schmitt, J.P. Schunck, T. Todorov, A. Zghiche*
CRN, CNRS-IN2P3/ULP/PHASE, Strasbourg, France

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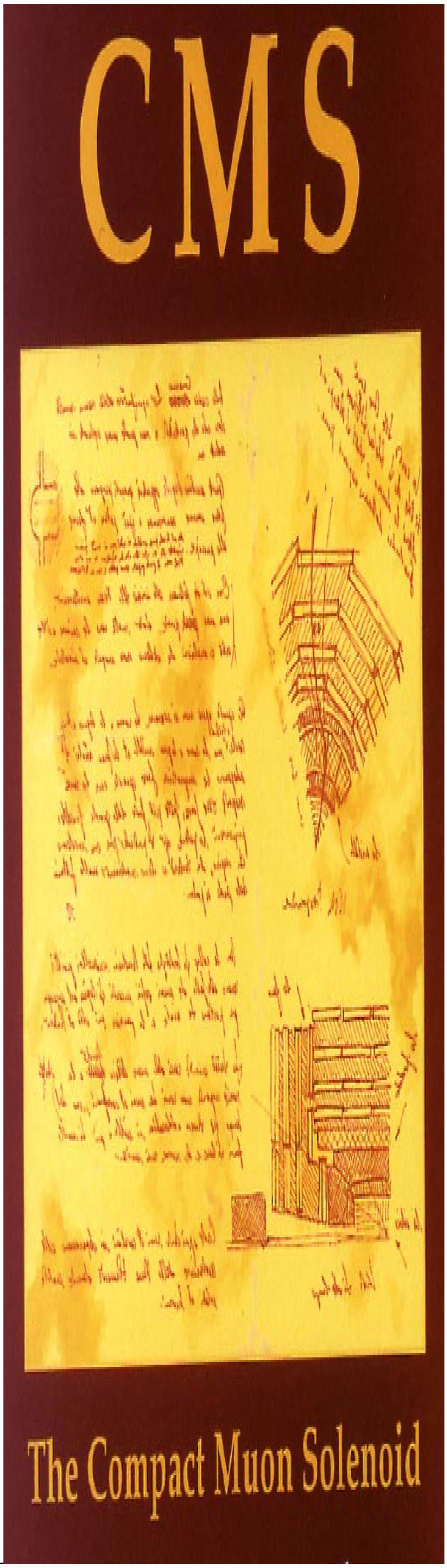
(*) Contact person
(1) On leave of absence Moscow State University, Moscow



INTRODUCTION

The purpose of this report is to summarise, in a single paper, the design and R&D efforts performed over the last three years to reach a possible approach for the construction of the CMS forward-backward MSGC tracker. For every conceptual design of a particle detector, several ways, in terms of mechanical design and construction procedures, exist to reach the desired goal. This report presents one such approach, and only those results relevant to the design presented here will be given. No attempt is made to compare this construction scheme to alternative possibilities that have been proposed. This summary also ends the R&D phase of the project, since the milestone prototype, due by the middle of 1997 should validate the construction scheme chosen.

I. GENERAL LAYOUT

The forward-backward MSGC regions of the CMS central tracker consist of 14 identical wheels on either side of the barrel part as illustrated in figure 1.
The detector area on each wheel extends in radius R from 515 mm to 1180 mm. The detector elements need to be positioned such, that this area is covered as completely as possible. The approach presented here consists of a modular system based on rigid gas boxes having the shape of a sector of an annulus ("banana") and housing between 7 and 10 individual MSGC detectors.

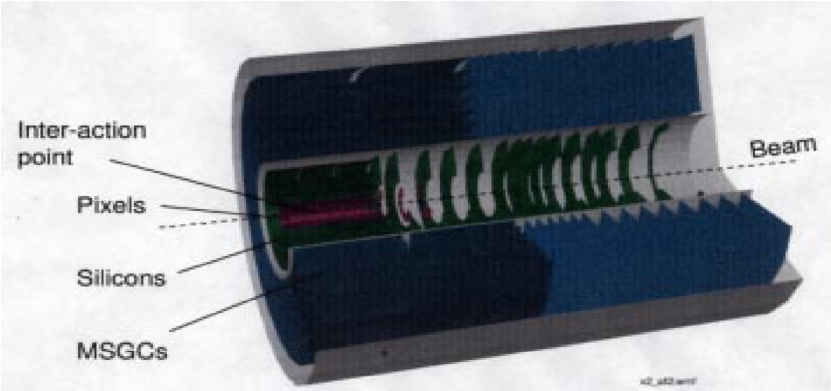


Figure 1 : General design of the CMS central tracker.

Figures 2 and 3 show how these boxes are arranged to form 3 concentric detector rings respectively on the front and the back of the mechanical support structure. All the "bananas" of a given ring are identical. The front and back rings are staggered in radius with an overlap in sensitive area ranging from 17 mm near the centre of the wheel to 22 mm for the two outermost rings. Full R coverage is hence ensured for high p_t particles. These overlaps in R can also be exploited for in situ alignment using beam halo muons. The boxes will be filled with MSGC's mounted side by side in the wall-less φ crack manner, forming a continuous detector surface of at least 70 cm and often more (up to 120 cm) along the circle concentric to the beam pipe. The distance between adjacent substrates is 70±10 µm whereas the anode pitch across the crack amounts to twice its value on the substrates. Limiting the dead space at the radial edges of the banana to 3 mm, including

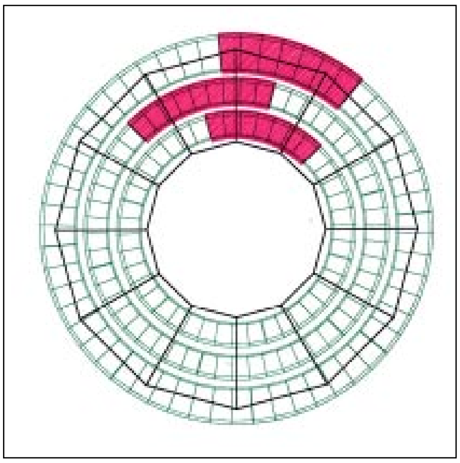


Figure 2 : The front side of a forward MSGC wheel.

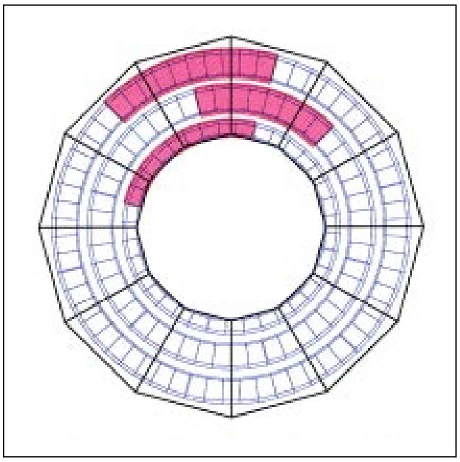


Figure 3 : The back side of a forward MSGC wheel.

the wall, is possible. Hence putting the banana boxes side by side will result in a dead space of about 6 mm or less than 1% of the detector surface. In φ the boxed are staggered in such a way that no projective φ crack exists from a ring to any other one. In the present layout the MSGC strips are radial, pointing to the centre of the wheel. In the outermost ring the anode pitch at the readout side (long base of the trapezium) is 249 µm and the striplength of the central cathode strip is 180 mm. All the substrates in the remaining rings have an anode pitch of 200 µm at the readout side. The central striplength is 115 mm except for the innermost ring where it is 47 mm.All the MSGC's have 512 anodes. Details about this general layout of MSGC detectors on a forward wheel are given in table 1.

Input	
PI	3,141593
b_anod	0,01
b_cathod	0,07
b_gap	0,06
phi-crack	0,07
Dead zone	6
#channels	512
RO hybrid	30
HV hybrid	25
PA depth	8
# hole/sub	1
d_tube	3

Ring	pitch	top_space	b_substr		overlaps active area	free space between boxes	between
1	0,249	127,639	127,569	back			
2	0,2	102,6	102,53	front	22,83051		
3	0,2	102,6	102,53	back	18,40833	14,09669	1-3
4	0,2	102,6	102,53	front	18,56783	18,50688	2-4
5	0,2	102,6	102,53	back	18,76904	18,33033	3-5
6	0,2	102,6	102,53	front	17,12575	20,00882	4-6

R=1180 end MSGC structure
R=516 start MSGC structure

Input			Calc'd									
			Active area		Substrate	Gas Rings				Cooling Rings		Boxes
# boxes	# sub/box	Lstrip	Ro	Ri	Ls	Ro	hole_dist	Ri	hole_dist	Ri	length	TopAngle
8	7	180	1144,88	963,0995	107,4811	1174,88	131,0515	935,0995	104,64	1152,88	905,4696	45
6	10	115	985,93	869,5945	90,55456	1015,93	105,7697	841,5945	87,93174	993,93	1040,841	60
6	9	115	888,003	771,5198	89,22973	918,0028	106,1253	743,5198	86,30107	896,0028	938,292	60
6	8	115	790,088	673,4204	87,57484	820,0876	106,5707	645,4204	84,26251	798,0876	835,7554	60
6	7	115	692,189	575,2859	85,44874	722,1895	107,145	547,2859	81,64115	700,1895	733,2367	60
4	9	47	592,412	543,1863	94,36493	622,4116	107,9309	515,1863	89,85743	600,4116	943,1244	90

Optim **param**

Positionerings variabelen						
l/l'=	DeltaR	Tophoek	Beginhoek	Patt.Hock top 70	Patt. Hock bottom 70	controle
1,002594	2,969296	6,3875	3,3474	6,3910	6,3917	45,04107
1,003229	3,183531	5,9611	3,1589	5,9651	5,9657	60,00412
1,003229	2,867328	6,6191	3,5077	6,6237	6,6243	60,00458
1,003229	2,551164	7,4405	3,9429	7,4456	7,4465	60,00516
1,003229	2,235054	8,4947	4,5015	8,5005	8,5017	60,0069
1,003229	1,912875	9,9288	5,2613	9,9355	9,9362	90,00699

Table 1

II. THE MECHANICAL SUPPORT STRUCTURE

The common mechanical support structure holding the 36 rigid "banana" boxes of one forward wheel consists of two concentric dodecagons linked by 12 radial spokes. It is assembled, by vacuum bag moulding against a flat surface, from standard carbon fiber struts of rectangular section 20 x 10 mm. These standard struts , from the Finnish company EXEL [1], are pultruded with 3 fiber orientations. The wall thickness of the tube is 1.3 mm. The 1995 price of these struts amounts to 24 CHF per meter for small quantities. The struts are assembled with custom made carbon fiber T like pieces. The rigid boxes are mounted on both faces of this dodecagon wheel leaving 10 mm space between the boxes on the front and back face. This space will be used for the cable routing (see section VII). The boxes of the outer ring are mounted on the outer dodecagon. All the other boxes are fixed on two radial spokes as illustrated in figures 2 and 3. The mechanical support structure has been fully modelled and a Finite Element Analysis (ANSYS [2]) has been performed to evaluate its mechanical stability, taking the manufacturer's specifications of the carbon fiber struts into account. Figures 4 and 5 show the modelling of the forward wheel indicating the nodes and cells used in the calculation.

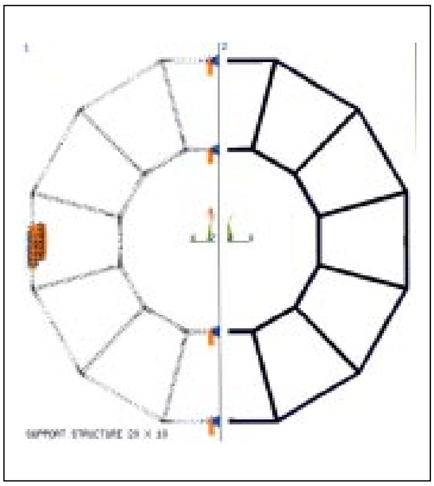


Figure 4 : Modelling of the forward wheel support structure.

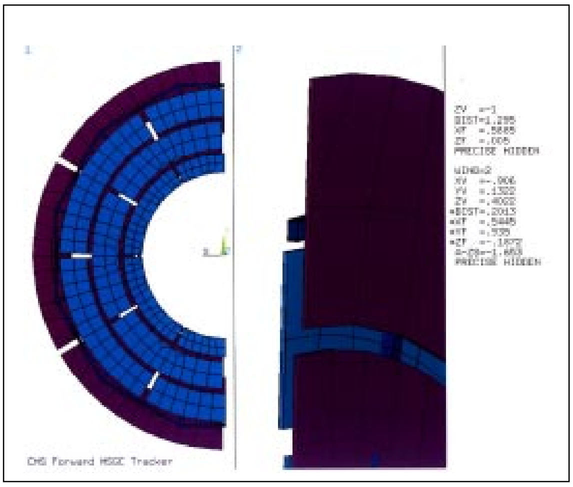


Figure 5 : Modelling of the forward wheel showing the cells for the fini te element analysis.

Under gravitation and taking the inclination of the LHC tunnel into account, the maximal displacements of the support structure fully loaded with the equipped "banana" boxes (kinematic free mounting) are :

$$U_x^{max} = 28\ \mu m;\ U_y^{max} = 57\ \mu m;\ U_z^{max} = 86\ \mu m$$

Where the y coordinate is vertically down and z along the beam.When the rigid boxes are fixed to the structure and therefore contribute to the stiffness of the entire wheel, the maximal displacements are found to be

$$U_x^{max} = 6{,}8\ \mu m;\ U_y^{max} = 11{,}6\ \mu m;\ U_z^{max} = 75\ \mu m$$

The total weight of the dodecagonal wheel amounts to 1,8 kg whereas the total weight of the 36 rigid boxes amounts to 13 kg of which over 4 kg is due to the glass (substrates and drift planes). The remaining weight is due to the boxes themselves and the ceramic hybrids holding the front end electronics and high voltage distribution.Section XI presents a Monte Carlo simulation showing the material in terms of radiation lenghts. In the case where the boxes contribute to the overall mechanical stability, it was investigated what the maximal displacements are for the worst "banana" box of the entire wheel.

They were found to be :

$$U_x^{max}=0{,}9\ \mu m;\ U_y^{max}=12\ \mu m;\ U_z^{max}=14\ \mu m$$

The result of this calculation is shown in figure 6.

Figure 6a : Maximal deformations along y of the worst banana on a forward wheel under gravitational load.

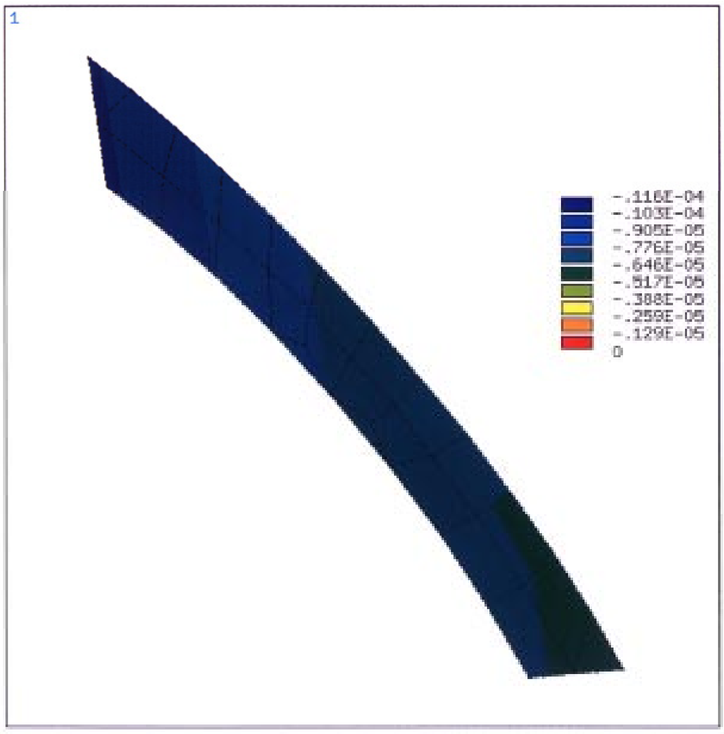
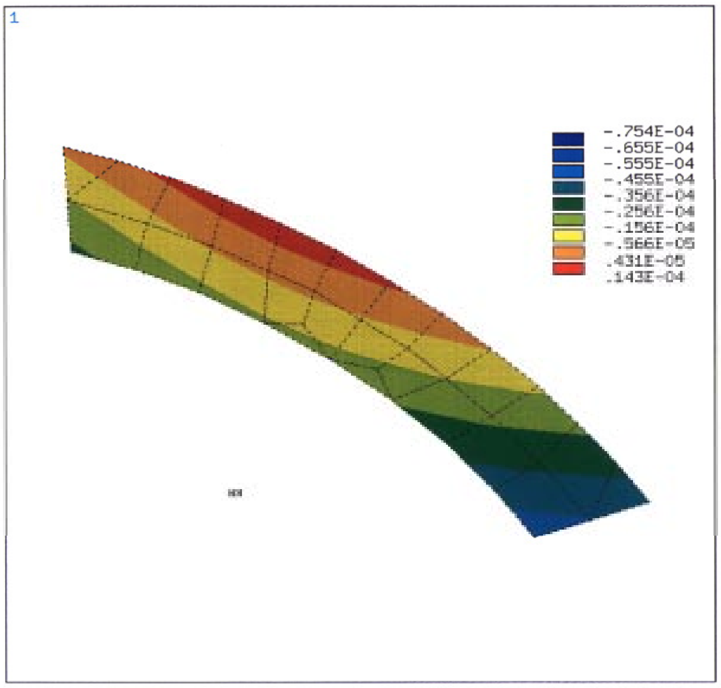


Figure 6b : Maximal deformations along z of the worst banana on a forward wheel.



III. THE FORWARD UNIT MODULE

Every "banana" box provides a common gas volume for the 7 to 10 adjacent MSGC counters mounted inside. The bottom plate of the box is an aluminium carbon fiber-honeycomb (or rohacell) composite structure. The carbon fiber shells sandwiching the 4 mm thick central core (honeycomb or rohacel) contain 4 orientations of unidirectional fibers each. The carbon fiber prepregs used are LTM25 ($80 g/m^2$) with a fiber diameter of 70 µm. An aluminium foil of 21 µm thickness is colaminated on both faces of the composite panel. Figure 7 shows schematically the lay-up of this composite structure.

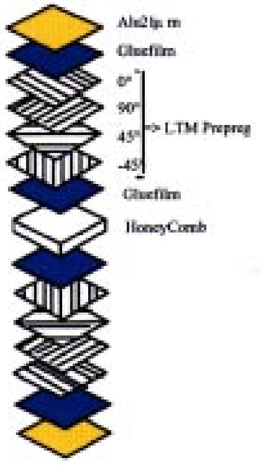


Figure 7 : Schematical lay-up of the composite panel.

Three full size (ϕ = 2,5m) discs have been manufactured and are shown in figure 8.

Two of them were produced by vacuum bag moulding between two 15 mm thick glass plates and cured in the autoclave at the SABENA plant.

Figures 9 and 10 illustrate this manufacturing process. The third disc was produced by the company EUROCOMPOSITE in Luxemburg using a heated press. Samples of the produced composites have been extensively tested (bending and tensile tests) to validate experimentally the Finite Element Calculations. Details about the composite structure can be found in two CMS Technical notes [3]. The composite panels are subsequently cut into "banana" panels of the correct size using a high pressure water jet or a milling tool.

Figure 8 : Picture of full size composite discs.

Figure 9 : Manufacturing the forward discs at the SABENA plant.

Figure 10 : Composite panel at the exit of the autoclave at the SABENA plant.

The curved edges of the gasbox are made of standard thin wall aluminium tubes of rectangular section 3 x 10 mm and wall thickness 200 µm. They are bent to the correct curvature and glued to the composite panel along their 3 mm wide side. They are also used as integrated gas distribution manifolds via laser-drilled holes facing every MSGC inside the box. The tube with the smaller radius ensures the parallel gas input to the MSGC's whereas the tube with the larger radius acts as the gas output manifold. Several gas boxes can be daisy-chained for simplified gas distribution (see section VII). The 1995 price for this standard thin wall tube amounts to 10 CHF per meter.

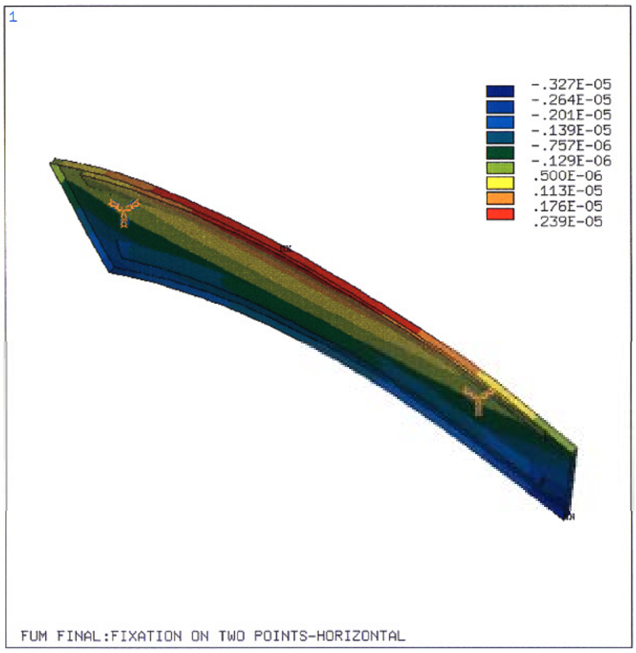


Figure 11 : horizontally fixed banana box.

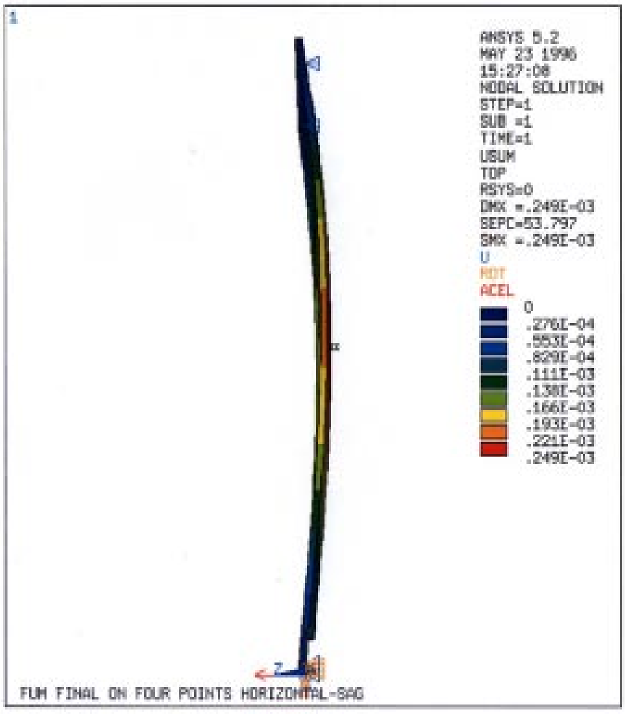


Figure 13 : banana box supported at the edges. Gravity acts left to right.

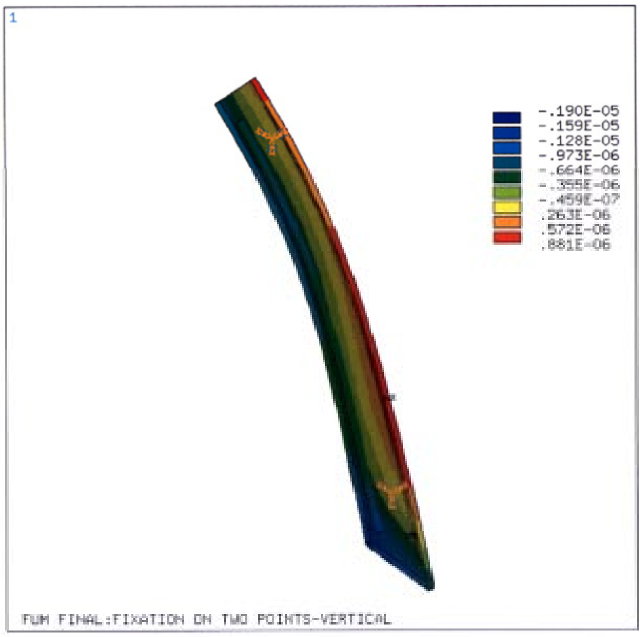


Figure 12 : vertically fixed banana box.

The radial edges of the gasbox are made of U shaped vectra or peek profiles. At the four corners of the box dedicated vectra or peek pieces allow for gas in- and output. The gasbox is finally sealed by an aluminised Kapton foil glued on top of the frame, the metalised side towards the inside of the box. Results of Finite element calculations of the box loaded with the detectors are shown in figures 11, 12 and 13. They yield negligible deformations under gravity, indicating easy and safe handling of the forward unit modules.

For the mounting of the MSGC detectors inside the gasvolume several options can be envisaged maintaining an identical overall mechanical structure of the forward wheel. Our preferred option is shown in figure 14. Here fully assembled and tested MSGC's are mounted side by side in the gas volume. The substrates are aligned and held in place in a stress-free manner using three excentrics (for details see section VIII).Cooling of the front end electronics is achieved by water flow through the thin wall aluminium tube, identical to the ones used for the gas manifolds, but glued along the 10 mm side to the composite panel. A detailed study of this cooling scheme is given in section VII. Data lines and electrical services to the front end hybrids are fed through the composite panel via a ceramic hybrid servicing two front end hybrids and connecting them to the optical modulator fixed at the back side of the panel. The flat Kapton pig tail of the front end hybrid is bump bonded to the feed through hybrid (~ 10 connections per MSGC) as schematically shown in figure 15. The main advantages of this approach are outlined in section IV. An alternative option, with the front end electronics outside the gas volume is shown in figure 16. Here all channels are fed through the gas barrier underneath the gas manifold tubes (double layer Kapton or Upilex). A third possibility, still with the same overall mechanics uses the substrates themselves as the feed through. The gas manifolds then require the use of an insulating material (e.g. vectra). A discussion of these different options is given in the next section.

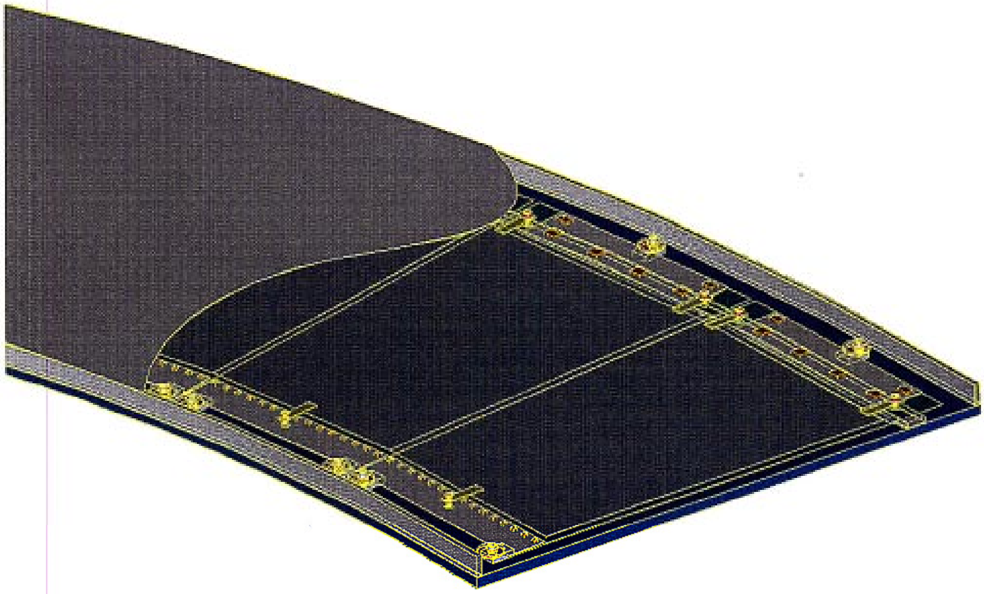


Figure 14 : Layout of a banana box with individual MSGC's mounted inside.

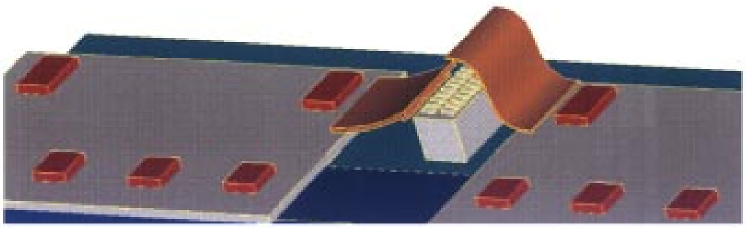


Figure 15 : Schematic of the ceramic feed through hybrid.

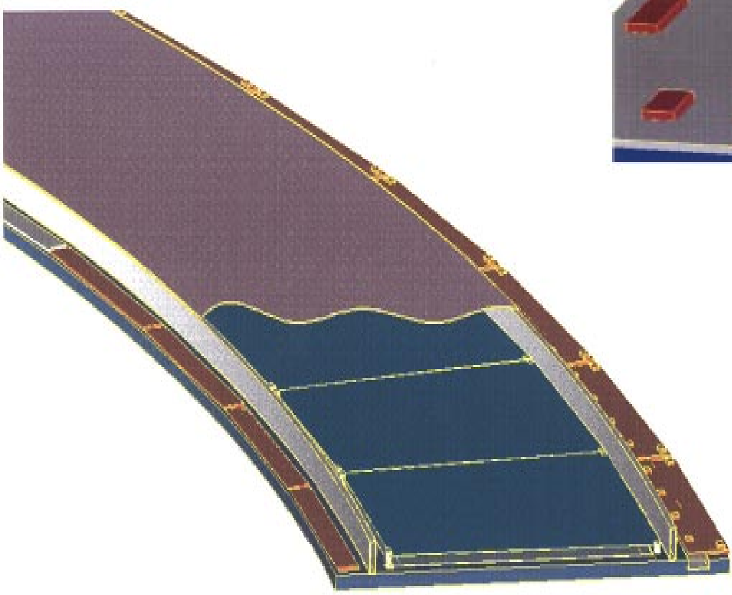


Figure 16 : An alternative layout with front end electronics outside of the gas box.

IV. FEATURES OF THE CONCEPT

In the first approach to equip the “banana” box with detectors, every MSGC remains a separate and individual item till the moment they are enclosed in the gas volume. This means that the detector construction, dominated by testing procedures and wire bondings, is performed on the smallest scale possible i.e. the individual substrate. This facilitates the handling and minimises the exposure time of naked substrates to dust. During the entire assembly and testing procedure of the individual counter, outlined in section VI, all parts remain accessible for intervention. Once a fully assembled MSGC is entirely tested in a remote gas box, it is stored in a clean environment until enough counters are available to equip one “banana” box. At this stage, the MSGC’s are mounted and aligned (see section VIII) inside the gas box which has been prepared remotely. From the experience gained with the realistic mock-up shown in figure 17, this procedure takes about 15 minutes per counter, hence minimising the exposure time of the MSGC’s. Once closed with the metalised foil, the gas box constitutes a protection of the fragile bonding wires and a complete and excellent Faraday cage to shield the counters and front end chips from pick up noise. Recovery or replacement of individual counters and/or substrates remains possible reducing the required spares to a minimum. It should be pointed out that no stress is put on the fragile and expensive glass substrate, neither by the gas pressure nor by any mechanical parts (e.g. frames) glued to it.

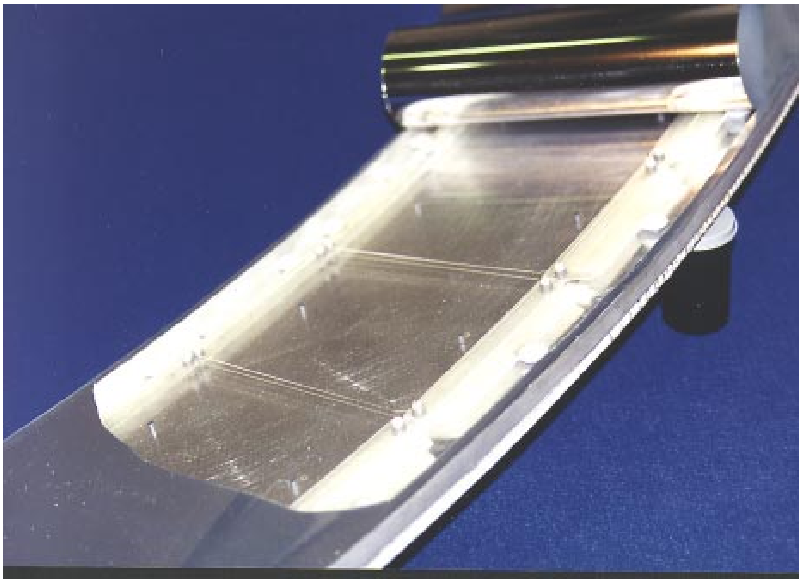


Figure 17 : Picture of a realistic mock-up banana. All assembly parts are the real materials. (composite bottom panel, 200μm glass, thin wall alu tubes, etc...)

In the second option (see figure 16), Kapton or Upilex pitch adapters are used as feed through. Provided they can be made with the required dimensions and precision this approach requires one extra bonding action to be performed inside the gas box. At least at this stage the entire box needs to be handled during the bonding operation increasing the exposure time of the MSGC’s substantially. The intrinsic protection and Faraday cage shielding of the front end electronics is also lost. Eventual recovery or replacement of individual substrates remains possible however at the expense of undoing the bondings to the pitch adapter.

For the third option, the MSGC substrates are glued to the bottom panel of the box. An adequate spacer frame is then glued across the substrates. A major worry resides in the stresses put on the fragile glass. All the bondings and electronic components are outside of the gas enclosure. Naked substrates are exposed during the alignment and glueing procedure but are then enclosed by the frame and drift plane prior to their connection to the electronic hybrids. A remote testing procedure is required since no access, recovery or repair of individual MSGC’s is possible after the glueing process. The protection and Faraday cage for the front end electronics is also lost unless extra material is added to maintain these features.

All our prototype activities have been performed in the spirit of the first option. The remaining sections in this report therefore exclusively concentrate on that approach although several designs or results can easily be transposed to either of the other options (e.g. servicing scheme).

V. THE INDIVIDUAL MSGC-MGC

In the entire forward and backward region of the CMS tracker the MSGC substrates have a trapezoidal shape. In the present layout the amount of fan in ranges from 10 to 20% depending on the ring. This narrowing is applied both to the cathode stripwidth and the anode-cathode gap , g, according to the rule developed by NIKHEF[4] to ensure uniform gain along the strips

$$g = p/8 + 20\ \mu m$$

where p stands for the interanode pitch. The anode stripwidth is constant, 10 μm for the outer ring substrates where the strip length is 180 mm and 7μm for the other shorter substrates. The artwork is performed on Desag 263 glass of 200μm thickness coated with a diamond like layer or a layer of semi-conductive glass. It has been shown [5] that such coatings improve the short and long term stability of MSGC counters. The artwork itself consists of gold strips for the long substrates (striplength 180 and 115 mm) and could be executed in chromium for the inner ring substrates (striplength 47 mm). It is also considered to manufacture the latter substrates, which are exposed to the highest particle fluxes, from semi-conducting (PESTOV) glass. For all the substrates, the cathode strips are connected per group of 16 to the high voltage bus via a 1MΩ protection resistor being a chromium meander integrated in the artwork. The readout and high voltage ceramic hybrids are glued to the glass extending beyond the bonding pads at the bases of the trapezium. The drift cathode consists of metalised Desag 263 glass of 200 μm thickness mounted in a removable manner at 3 mm above the substrate. Figure 18 shows the design of such an individual MSGC counter.

Figure 18 : Assembly of an individual forward MSGC.

Half of the forward wheels are expected to measure space points instead of only the φ coordinate. Our baseline choice for these measurements are Micro Gap Counters (MGC) with a suitably patterned cathode plane [6]. The assembly of such counters would be identical to the standard MSGC's but would require a different layout of the read out and high voltage hybrids. The overall mechanical structure remains however unchanged.

VI. CONSTRUCTION AND TESTING PROCEDURE

The procedure outlined below has been largely inspired by the MSGC production procedure adopted at NIKHEF for the SMC experiment at CERN [7] and the HERMES experiment at DESY [8]. For the former experiment a system of 16 rectangular MSGC's with 512 channels each and a strip length of 100 mm has been built. Four such counters are enclosed in a common gas volume with the front end electronics (APC chips) inside. In the latter experiment, the largest MSGC system built so far is operational. It consists of 52 MSGC's of ≥ 512 channels and strip lengths up to 180 mm. The substrates are rectangular or have the shape of a parallelogram. Up to 6 open counters are mounted side by side in the wall-less φ crack manner. The MSGC's are enclosed in two gas boxes housing 26 counters each. The following sequence of steps have been adopted during the construction of both these systems :

1) Cut the glass substrate and perform final cleaning (this step could be performed at the substrate production plant)
2) Optical inspection of the artwork
   (Microscope, Projection table or automated device)
   - Look for "mouse bites", "blobs", shorts, interruptions, etc.
   - At this stage a substrate could be rejected if too many faults are detected
   - This procedure could be complemented by an electrical test.
3) Possible repair of shorts ⇒ back to 2)
   (Removal using N_2 laser)
4) Protective cover over the substrate with the exception of bonding pads
5) Glue tested hybrids to the substrate
   (Readout and High Voltage side)
6) Perform all the bondings from the substrate to the hybrids
7) Removal of the protective cover
8) High voltage test of the substrate in dry N_2
   (Monitor dark current, remove possible dust particles by blowing Ar or by dedicated vacuum cleaner)
9) Mount the drift plane
   (In a removable manner)
10) Test unit detector in a dedicated provisional gas box
    (This is the final test of a fully operational detector; i.e. a test of everything)
11) Mount detectors in the banana gas box, align them and retest HV.
12) Close the banana gas box
13) Final test of full banana before storage or shipment
    (At this stage all interventions and recovery of substrates are still possible)

The following steps are performed in the clean room : [2-4] ; [7-9] and [11-12]. Apart from the mounting of the tested detectors into the banana box, all operations are performed on the level of a single substrate and therefore do not require a large clean room or bulky equipment.

Using such an assembly and testing procedure, the yield of accepted operational counters with less than 1% failing channels was 80% for the HERMES experiment. However more than 10% of the delivered substrates was rejected during step 2) reflecting the skill of the manufacturer of the substrates (SRON Netherlands). It has to be pointed out that no excessive (expensive) quality control has been performed by the manufacturer. After the running in period, the assembly and testing turn over for these large area MSGC's was 2 man days per counter using exclusively manual bonding machines.

VII. THE SERVICING SCHEME

Several services have to be provided to the MSGC detectors.The heat produced by the front end electronic components has to be evacuated by some coolant flow. The detectors also require the suitable gas mixture to be distributed to all of them. In terms of electric services, every detector requires high voltage on the cathode strips (≈ - 600 V) and on the drift plane (≈ - 2000 V). Furthermore, the front end electronics requires the low voltage bias to be applied and finally electronic signals have to be brought to and extracted from the MSGC's. An optimised design of these services is of utmost importance keeping in mind the contradictory conditions being the reliability of a "no access" system and the material budget of the entire tracker. Any "overkill" to meet the first condition immediately translates into an increase of material. Although further work is required to work out the details of an optimised servicing scheme, some initial ideas, calculations and measurements are presented here.

a) Cooling

The scheme that has been evaluated is based on water cooling using the "leak-less" system where underpressure ensures the liquid flow. As shown in figure 14, the cooling pipe is integrated in every banana box and consists of the standard thin wall (200μm) aluminium tube with rectangular section of 10 x 3 mm^2. The in and outlets are fed through the bottom panel of the box. The calculations and measurements were performed for a scheme where half a detector ring is cooled by the flow through serially interconnected bananas. A single pipe brings the coolant to a 12 fold manifold on top of the forward wheel. Each channel cools a half ring and is evacuated via a manifold at the bottom of the wheel and a single pipe leaving the tracker volume.Gravity is therefore exploited to ensure the water flow through the "leak-less" system. Within each banana box the heat sources (front end chips) are coupled to the heat sink (cooling water) by simple direct mechanical contact between the substrate carrying the front end aluminium oxyde hybrid and the 10 mm wide side of the aluminium cooling pipe. The performance of such a simple (cheap) cooling scheme has been evaluated through finite element calculations and measurements, and is described in detail in a CMS technical note[9]. Only the major results are summarised here.

The following boundary conditions have been taken :

- Flow rate of the demineralised water : 0.2 m/s
  yielding a safe laminar flow
- Volume of the front end chip : 6 x 6 x 0.5 mm^3
  about the anticipated size of the APV6
- Heat production for a 128 channel chip : 256 m Watt
  corresponding to the anticipated power consumption of 2 mW per channel

The FE calculations then yield the following results :

ΔT (water) along 1/2 outer ring (3.8m)	≤ **1.5° C**
ΔP for horizontal flow	≤ **1.3 k Pa**
ΔT (heat source-water) for perfect contact	≤ **2.5° C**
ΔT (heat source-water) with 10μm "air gap"	≤ **5.6° C**

The set-up for the measurements performed at CERN is schematically shown in figure 19 and a typical measurement of cooling performance is shown in figure 20 confirming the ΔT of less than 6° C.

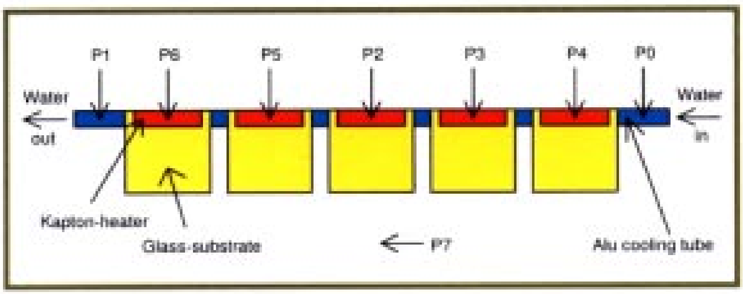


Figure 19 : Shematic of the set up used for the study of cooling performance

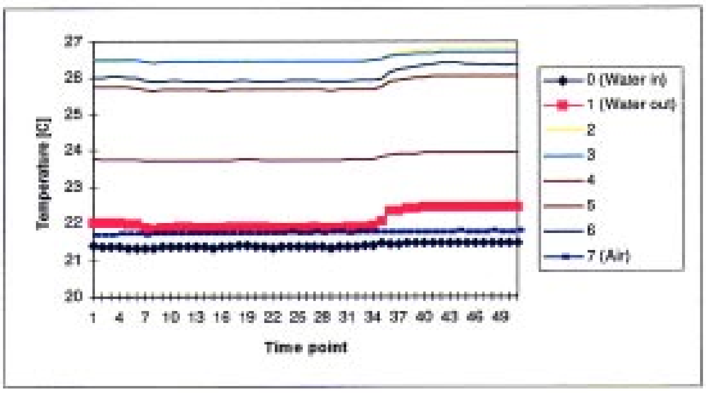


Figure 20 : Readings of the temperature sensors as a function of coolant flow rate.

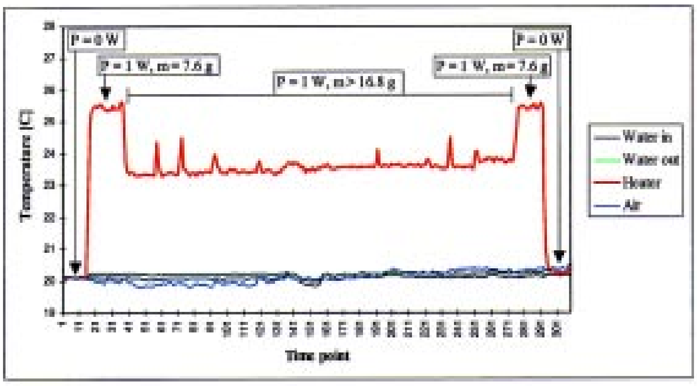


Figure 21 : Influence of contact pressure on the cooling performance.

The influence of the contact pressure is shown in figure 21 showing no further improvement beyond 16,8g.

It should also be noticed that no temperature increase was found for the air enclosed inside the thermally insulated measurement box. Indeed with this cooling scheme it was calculated that only 4% of the heat load would be taken away by the detector gas. Finally an attempt was made to increase the quality of the thermal contact by introducing thermal grease (Dow Corning 340) between the cooling pipe and the glass substrate. This resulted in a reduction of the ΔT by only 1° C and is therefore considered as a superfluous complication.

b) Gas distribution

Calculations have started to evaluate a minimal gas supply scheme (in terms of material budget) considering a single supply and evacuation pipe (ϕ= 4 mm) per forward wheel. It is schematically shown in figure 22 and consists of a high impedance, fully parallel supply to the individual MSGC detectors. The gas mixture is fed to and evacuated from 12-fold manifolds integrated in the wheel support structures situated at 0° and 180°. Half of the banana boxes of each detector ring are daisy-chained putting their integrated gas manifolds (input at small radius; output at large radius) in series. The gas is distributed inside the box through holes facing every MSGC. These holes are laser drilled into the thin wall alu tubes that constitute the integrated input and output manifolds of the banana box (see figure 14).

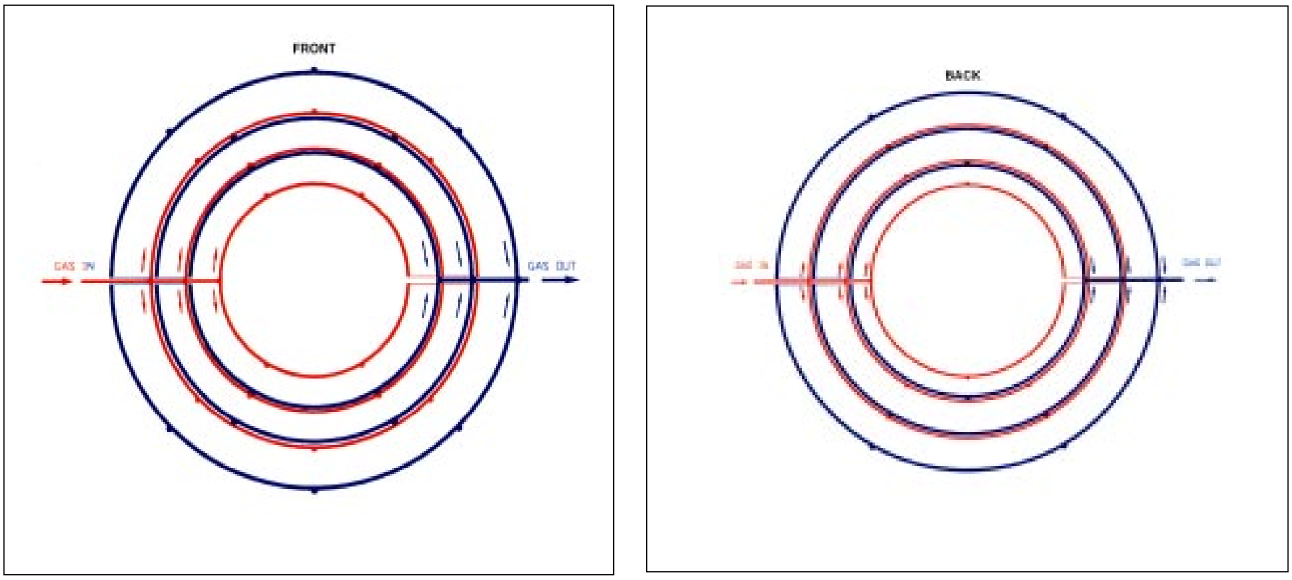


Figure 22 : Schematical layout of the gas distribution for one forward MSGC wheel.

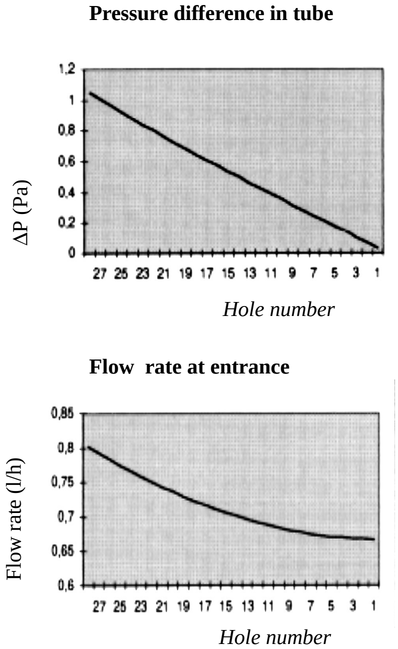


Figure 23 : Pressure drop and flow rates for the gas distribution in 1/2 detector ring.

Preliminary calculations shown in figure 23 show that pressure differences remain extremely safe even if 10 gas renewals per hour are envisaged. This allows the input holes to be dimensioned in such a way that uniform flow (within 10%) to all detectors in a half ring can be ensured even at low flush rates.

These minimal schemes for fluid servicing (one supply/wheel) were shown to be adequate. To cope with possible trouble shooting (e.g. leaks) an increased modularity may however be desirable, and can easily be integrated.

c) Electrical services

The MSGC operation requires two negative voltages to be supplied; one up to about - 600 V to the cathode strips and one of about - 2000 V to the drift plane. The former bias determines the gas gain of the detector and may require independent tuning by about 10 to 20 V at the level of individual substrates. In collaboration with CAEN, the Pisa group develops a system to monitor and control this high voltage on the HV-hybrid connected to the substrate. If successful, the same scheme could be adopted for the forward MSGC wheels. This system could be complemented by a protection scheme against shorts as schematically represented in figure 24. Here a fuse resistor (~ 300 Ω) is integrated in the anode bonding pads. It consists of a 50 x 500μm^2 thin film of Nickel-Chrome (the adhesion layer for the artwork metalisation). When a short develops, in situ fusing of the shorted anode resistor would be obtained by reversing the polarity of the cathode voltage. A diode in parallel with the cathode protection resistor (1 MΩ per block of 16 cathodes) allows the current to flow and to find its way to the correct fuse via the short. The experimental optimalisation between fuse surface, required current and preshape 32 input protection is being pursued.

The drift voltage does not require fine tuning and could be applied with a modularity of one supply per banana box (7-10 MSGC's).

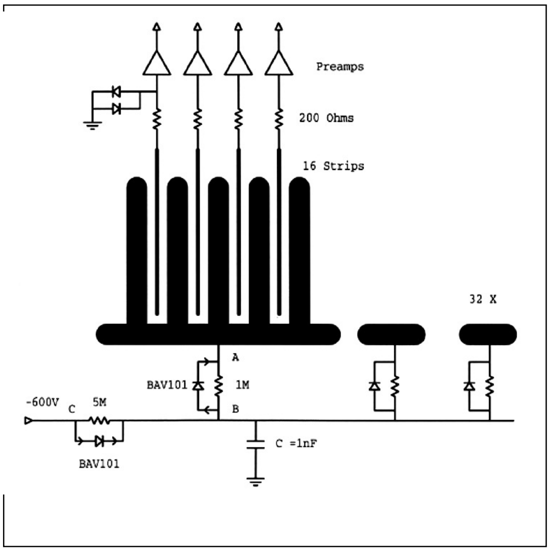


Figure 24 : Short protection scheme.

The servicing of low voltage to the front end chips constitutes the main worry in terms of material budget. The degree of daisy-chaining possible will be investigated when close to final chips (preamps and control chips) are available and the final front end ceramic hybrids are developed. A modularity of one supply per banana looks feasible but requires further investigation.

Finally control signals have to be provided to the front end chips (e.g. clocks) and the detector signals have to be transferred to the counting rooms. CMS has opted for optical transmission. At present it is expected that a single opto coupler could service 8 chips of 128 channels each. The opto couplers would be fixed to the back side of the banana box near the feed through hybrids situated in between two front end MSGC hybrids (cf. figure 15). The fibre bundels would be routed radially outwards in the space (1 cm) left between the front and back bananas of the forward wheel. All other electrical services can also be routed within this space.

VIII. ALIGNMENT, MONITORING AND MAINTENANCE

Due to the modularity of the detector system, a two stage alignment has to be adopted at the construction phase : the alignment of counters within every banana box and the alignment of the boxes on the forward wheel. The artwork on the substrate benefits from sub-micron precision. At present, the alignment scheme adopted here, refers directly to this artwork rather than relying on the edges of the glass. It remains indeed to be proven that the glass can be cut with a precision of less than 10 µm with respect to the strip pattern. For the alignment of the MSGC's within the banana box, two requirements have to be fulfilled at the assembly stage :

i) All the strips are radial(*)

ii) The anode pitch across the cracks between adjacent counters is twice the nominal pitch on the substrate.

This can be achieved using a single high precision jig per type of banana box (6 in total). The jig is used to transfer with the required precision (5 - 10 µm) the box frame, the fixation pieces, the alignment pins and the external fiducial marks to the carbon fibre panel in a single glueing operation. A schematic layout of such a jig is shown in figure 25. The use of a precision jig, at a fixed temperature, ensures all the bananas of a given type to be identical, hence reducing substantially the number of alignment constants to be kept in a database. Two alignment pins per MSGC are positioned by the jig along a radius of

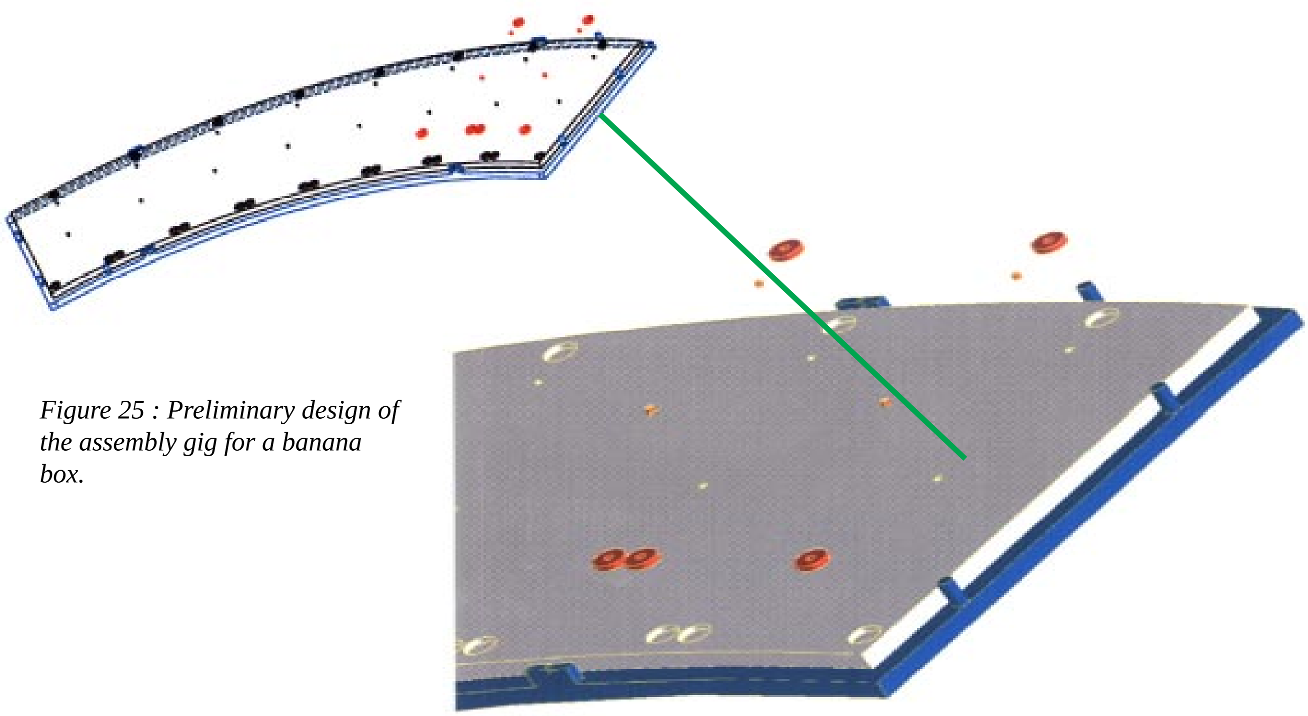


Figure 25 : Preliminary design of the assembly gig for a banana box.

the wheel and glued to the rigid bottom panel of the box. They consist of small cylinders (Φ = 3 mm, h = 3 mm) with a hole drilled along their axes. At the upper part, this hole has a diameter of only 120 µm.

(*) It has been suggested[10] that some measurement of the R coordinate may be achieved if successive forward wheels have their strips at a small stereo angle w.r.t. the radial direction e.g. + and - 50 mrad. This can easily be achieved, without increasing any tooling, by alternating the front and the back sides of successive forward wheels.

Subsequently the MSGC is aligned under a microscope by centering the fiducials printed in the central cathode strip into this small hole. Precision movement of the MSGC is obtained by turning two excentrics against one base of the trapezoidal substrate. The MSGC is then kept in place by blocking the excentric lips while a third excentric is adjusted against the other base of the substrate and also blocked. This alignment procedure

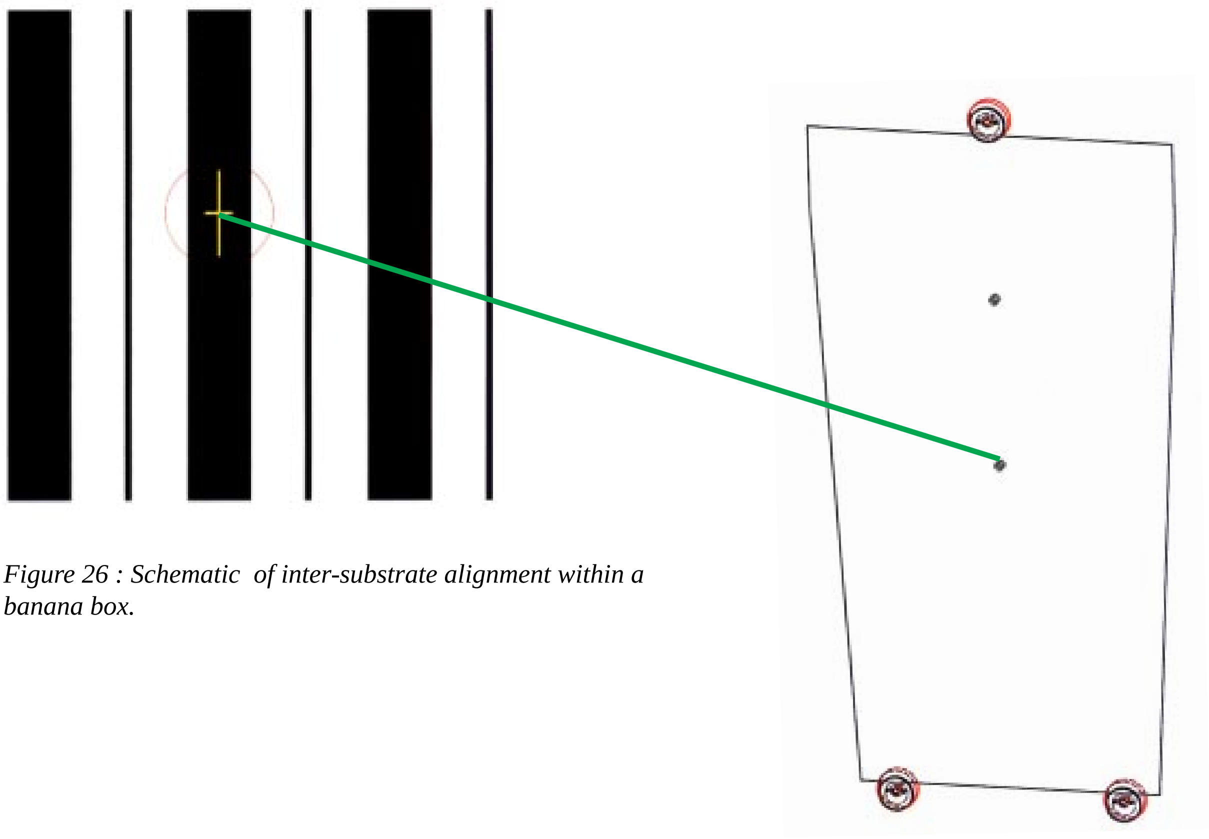


Figure 26 : Schematic of inter-substrate alignment within a banana box.

is schematically illustrated in figure 26. Alignment of the 36 banana boxes on the dodecagonal support structure is then based on the external fiducial marks of the boxes. They are directly related to the strip positions via the precision jig. The interalignment of the forward wheels could be based on a light source - CCD camera system similar to the one proposed for the barrel tracker[11].

Control and monitoring of the alignment will be achieved in situ using halo muons and particle tracks. Here the overlaps in R between adjacent detector rings and the j staggering of banana boxes on the front and the back face of the wheels will be exploited. Other monitoring tasks embedded in the MSGC slow controls system are beyond the scope of this report since they interfere little with the specific detector layout presented here. They are however of utmost importance and need to be developed in close collaboration with the barrel MSGC system of CMS.

The maintenance of the forward MSGC system will be based on spare banana boxes of every type. Access to the central detector will be rare and extremely difficult. Getting at any banana box is far more difficult and time consuming than its eventual repair. However in the scheme presented here, a faulty banana can, after replacement by a spare one, be easily opened and repaired by replacing the faulty individual MSGC. The good detectors within the module are therefore not lost. This feature may turn out to be of importance to keep the cost of spares under control since at present the failure rate of the MSGC's is still largely unknown.

IX. PROTOTYPE RESULTS VALIDATING THE APPROACH

The following questions, related to the specific design presented in this report, will be addressed in this section :

i) Does the joining of substrates work ?
ii) Does the gas volume constitute a problem ?
iii) Does outgassing of the electronics influence the MSGC lifetime ?
iv) Do long term effects of the counter gas on the electronics exist ?

i) The performance across the gap between two neighbouring counters

An essential feature of the design of the forward MSGC tracker consists in joining several substrates side by side in a common gas volume. A prototype to test this feature has been built[12]. The test substrate was made from a usual 10 x 10 cm^2, 512 channel MSGC similar to those used by SMC[7]. A piece of substrate with 2 blocks of 16 strips was cut from the center and the two remaining pieces of substrate, ending by a cathode strip, were placed side by side at a distance of 70 µm. The distance between the first anode strips adjoining the crack was twice the nominal pitch of 200µm as illustrated in figure 27.

This prototype, together with a normal MSGC was put in a gasbox filled with a 50-50 Ne/DME mixture. The counters were put into a cosmic ray telescope, shown in figure 28, which selected minimum ionising muons, reconstructed their tracks and predicted the impact point on the MSGC's.

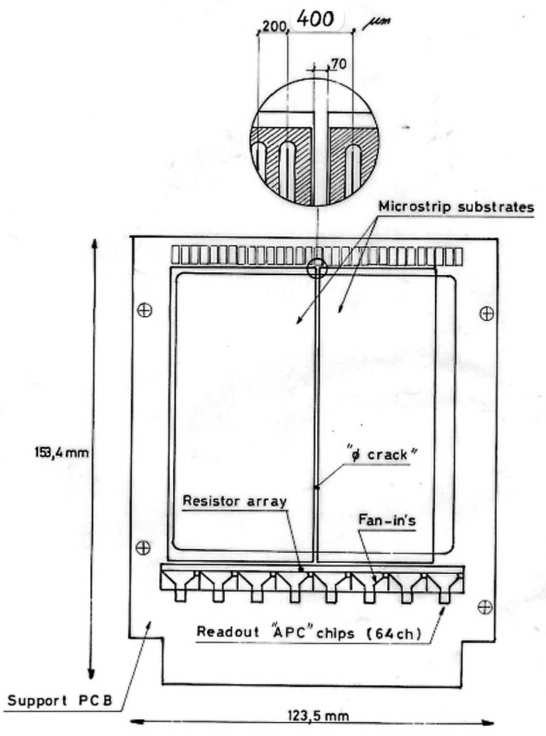


Figure 27 :Layout of the wall-less φ crack prototype.

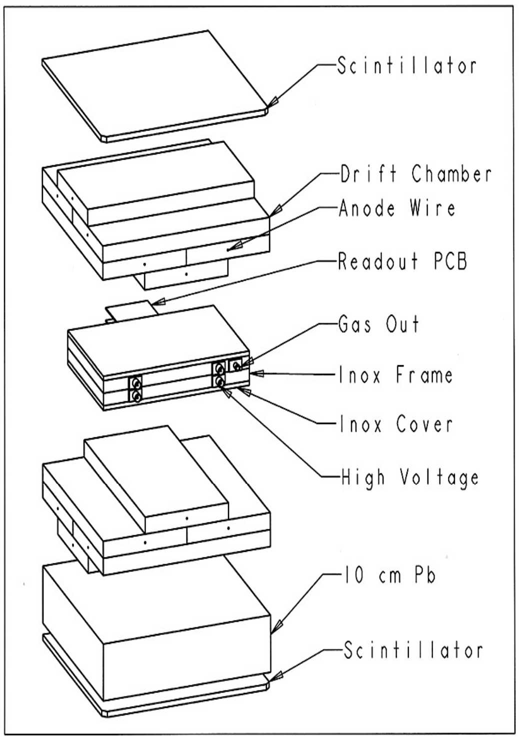


Figure 28 :The cosmic ray telescope.

Figure 29 presents the efficiency of the test counter measured across the crack for perpendicular tracks. The efficiency is constant at a level of 98.5%. The absence of a dead zone was predicted, as the electric field near a missing anode strip deviates the drifting electrons to the neighbouring anode strips. This effect has been observed many times at the position of broken anode strips. An illustration of this behaviour is given by a measurement using a Sr90 source. Figure 30 shows the source profile as seen by the detector in a region with all anodes working and the same profile in a region where one anode strip was removed. It is observed, that strips next to a removed anode collect much more signal than normal. A second experiment[13] with three MSGC's, of which the middle one had a φ crack, was performed in the cosmic ray hodoscope. It was found that the resolution for close to normal incidence (- 4° to + 4°) in the crack region is 70 µm, nearly twice the resolution of 36 µm found in the homogeneous areas for normal incidence. It has to be noted however, that a strip in the region close to the crack was dead (not the immediate neighbours). This position resolution found can hence be regarded as an upper limit. A level difference of about 200 µm between the two adjoining substrates may also contribute to the deterioration observed.It should also be noted that the above prototypes have been operated during two years with less than 1 trip per week (trip level 8o nA).

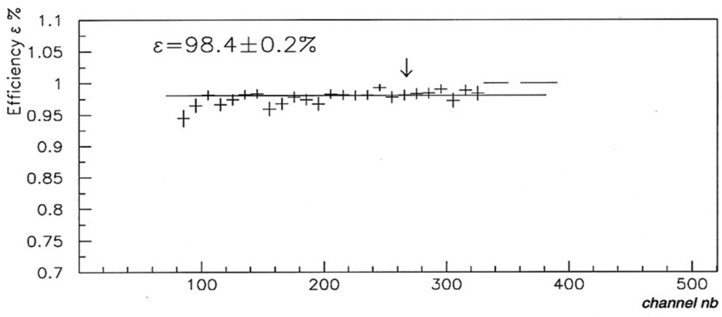


Figure 29: Efficiency versus channel number in the φ crack prototype. The location of the crack is in channel 260.

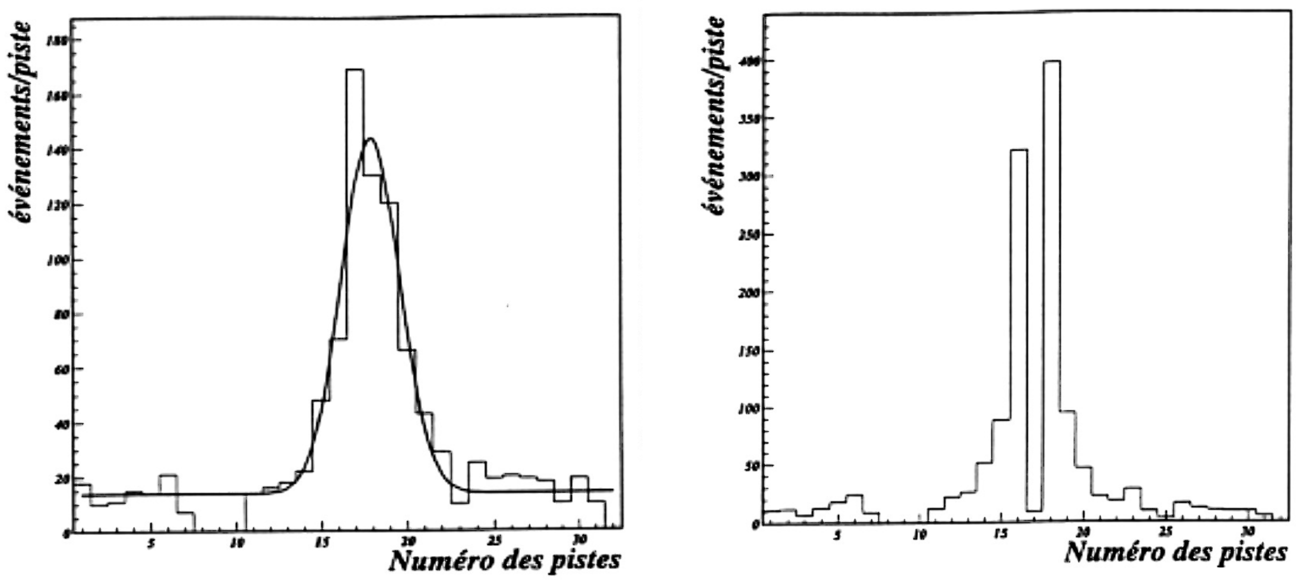


Figure 30 : Sr 90 source profile across a φ crack.

The same arrangement of substrates joint in a common gas volume has been used in the vertex detector of the HERMES experiment[8]. No problem related to this layout was encountered in the operation of these detector planes during the first year of running at DESY.

For the September 1995 beam test of the CMS tracker in the X7 beam at CERN, two “mini banana” detectors of the design presented in this report have been built and operated[14]. The

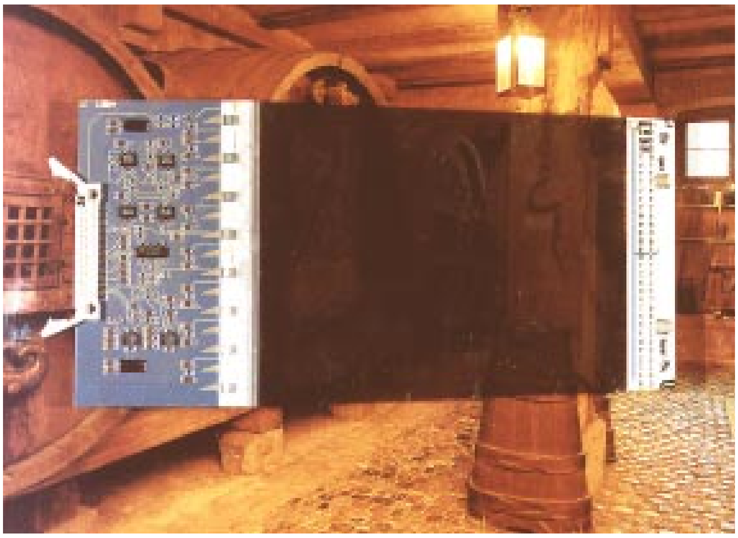


Figure 31; Picture of a wedge shaped MSGC connected to the readout hybrid before insertion in the "mini banana".

prototype produced at Strasbourg contained two side by side wedge counters with 512 anodes each. The pitch at the long base was 200 µm reducing to 180 µm at the short base. The length of the central strip was 120 mm. Figures 31 shows such an individual MSGC before insertion into the light weight gas box.

The prototype constructed in Brussels also had two 512 channel substrates assembled with a wall less φ crack. Here the anode pitch varied from 241 µm to 186 µm. The strip length was 116 mm. In both cases the metalisation was aluminium on bare Desag glass. A common read out ceramic hybrid was developed in Strasbourg for the APC front end chips[15]. The Brussels prototype had 768 connected read out channels, the Strasbourg one had 64 channels read out on either side of the crack. Figure 32 shows a picture of the Belgian prototype where the carbon fibre - honeycomb bottom panel is fixed to the standard frame for the beam test.

Both prototypes were mounted, one behind the other, in the test beam. Figure 33 shows the signals produced by a beam particle crossing both detectors. DAQ and Si telescope problems prevented us from gathering a sufficient amount of good quality tracking data. Both prototypes were however operated in stand alone mode for 10 days with the cathode voltage set at - 550V and the drift plane at -2200V.

With a trip level set at 80 nA the average trip occurrence was 1 per 24 hours using a 50-50

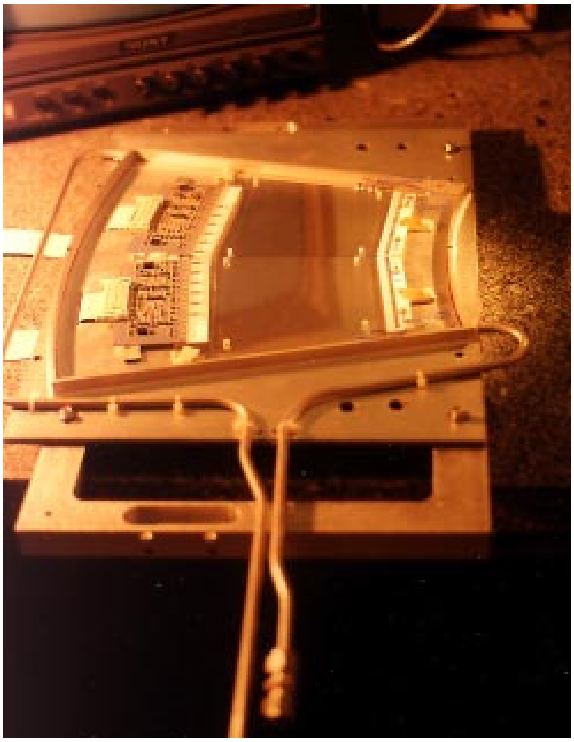


Figure 32 : Picture of a "mini banana" for the september 1995 beam test.

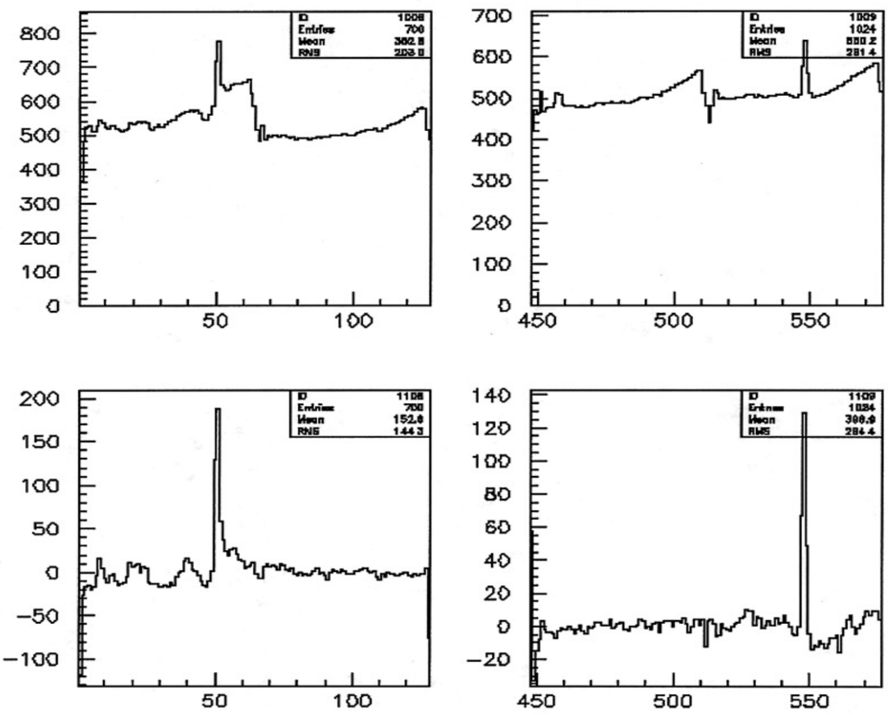


Figure 33 :Beam particle crossing the successive prototypes. Bottom figures with pedestals and common mode subtracted.

Ne/DME gas mixture.This rate, higher than usual, was due to the lack of conditionning of the prototype, the shortened construction procedure, and the absence of a clean room for assembly. The measured gain was 3700 yielding a S/N ratio of about 30. Figure 34 shows the gain variations along the anode strips of a wedge shaped MSGC.

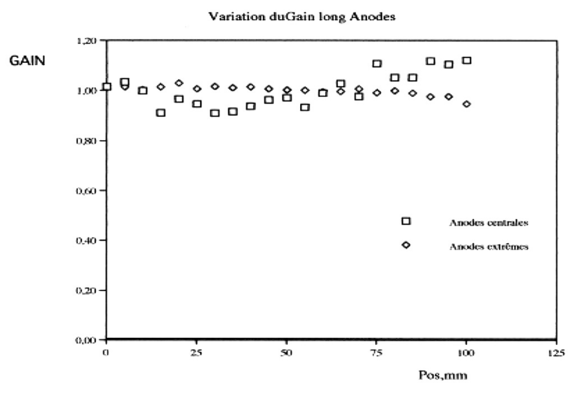


Figure 34 : Gain variation along the strips of a wedge shaped MSCG for central anodes and anodes near the edges .

ii) Gas composition

The favoured gas mixture is currently composed of neon and dimethylether. Neon is expensive hence the gas cost is largely determined by the quantity of neon used. It was shown in the cosmic ray hodoscope that the performance of 20-80, 40-60 and 50-50 Ne/DME mixtures is quite comparable in terms of efficiency, spatial resolution and plateau length[16]. Recently a comparative study has been undertaken in the same set up to compare the performance of argon, neon and helium as additive to DME. Pure DME is being investigated as well. Preliminary results indicate[17], that the length of the HV plateau with constant high efficiency is only 30V before break down (80 nA) in Ar/DME, whereas in identical conditions it is more than 60V in mixtures of DME with neon or helium. It is 80 V in pure DME.

The length of the plateau is very important for the successful operation of large systems, as time between breakdowns is a very sensitive function of the distance of the operating point to the break down voltage. The same distance determines the frequency of micro discharges responsible for tripping.

iii) Outgassing of electronics

Presently a small banana like the one shown in figure 32 is under test in the ageing set-up at CERN. Two MSGC's of 512 channels and 8 cm strip length are mounted inside. The substrates are the ones developed by the CERN-PPE-GDD group and consist of one gold and one chromium strip pattern on diamond like coated (SURMET) Desag 263 glass. The drift planes consist of gold plated glass of 100 µm thickness, mounted 3 mm above the substrate using small cylindrical (Φ = 3 mm, h = 3 mm) vectra spacers. A complete ceramic hybrid with 8 working preamplifier chips (APC) and associated circuitry (surface mount components and several operational amplifiers) is also situated inside the gas volume. No cooling is applied to the electronics. Figure 35 shows the relative gain versus the accumulated charge per cm of striplength for the gold substrate. An initial drop of 5% is observed, correlated with some outgassing during the initial powering up of the electronics. No ageing is observed so far. The experiment continues.

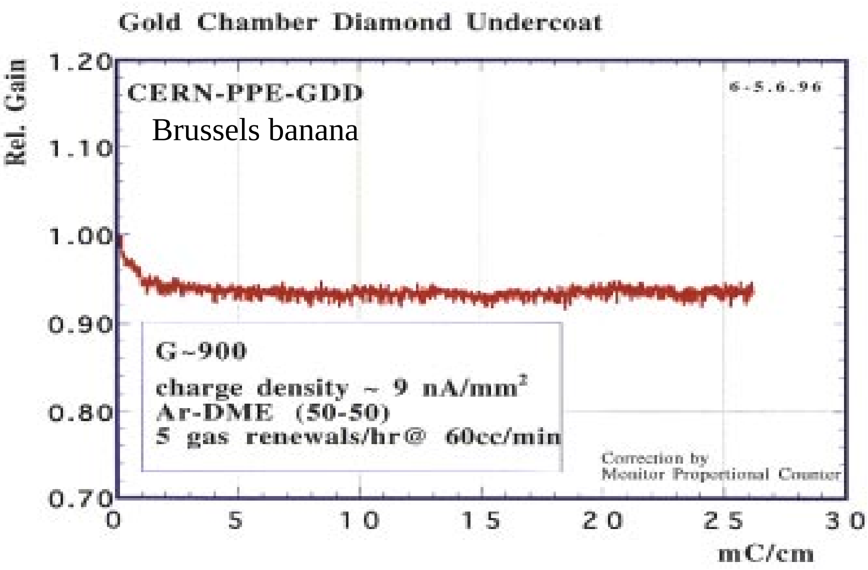


Figure 35 : Relative gain versus accumulated charge in the ageing test of a "mini banana".

iv) Long term effects of counter gas on electronics

The longest exposure to date is done in the SMC experiment, where 16 MSGC's of 512 channels each have been operated for more than two years of running at high intensity. Initially the gas composition was CO2/DME 60/40, after one year this has been changed to Ne/DME 50/50. The preamplifiers (APC) and related electronics (line driving) are operated inside the gas. No change in the functioning and the noise levels of the preamplifiers have been observed over this entire period. Several other set ups are operational with the front end electronics inside DME based gas mixtures. Some for a shorter period (eg. Hermes) or some at lower intensity (eg. cosmic ray hodoscope in Brussels). Not the slightest indication of deterioration has been observed.

X. ONGOING DEVELOPMENTS

The ongoing developments now concentrate on the preparation of the production of the substrates themselves. For MSGC's the state of the art for long term reliable operation at high rates, Diamond like coatings and Gold or Chromium metalisation seem mandatory[12]. In collaboration with VITO(*) and NIKHEF, diamond like overcoatings of good quality (stability) and required surface resistivity (10^{15} - 10^{16} Ω/□) have already been produced and tested on small samples (5 x 5 cm^2). A programme has been launched to produce undercoating (VITO) and Gold artwork (SRON(**)) on larger substrates. For final mass production VITO possesses a continuous production line of up to 5 vacuum chambers in which substrates of 15 x 30 cm^2 could be treated in successive steps without breaking the vacuum. Those steps could be : cleaning of glass, plasma cleaning, diamond like coating, metalisation of adhesion layer, metalisation for the artwork (Au). The continuity of the process within the same vacuum will vastly reduce the problems of dust particles. In France first samples of diamond like coatings have been produced at ICMC and show adequate quality.

As mentioned before, the baseline choice for the measurement of space points (half of the detectors), is the Micro Gap Chamber. In close collaboration with IMEC(***), an R&D effort is in progress to produce cheap and radiation hard MGC substrates. The choice of the spincoated dielectric put forward by IMEC is Benzo-Cyclo-Buteen (BCB) because of its intrinsic radiation hardness (tested to few Mrad). At present the cathode and anode metalisations are aluminium because of the simple etching procedure. Gold metalisation is of course possible but would boost the price upwards, since also the etching process is much more involved. If it turns out that for reliable long term operation the aluminium needs to be inhibited, a thin layer (~ 300 Å) of chromium or gold could be added on top. First working wedge shaped MGC's of 8 cm striplength are expected to be tested soon. Figure 36 represents schematically the MGC design pursued at IMEC where passivation of critical regions is integrated into the 3 mask process. Figure 37 shows pictures taken with a scanning Electron Microscope of an MGC produced at IMEC. A collaboration between PHASE (Strasbourg) and OPTIMASK also aims at producing MGC substrates using spin-coated polyimide. First samples have been tested successfully.

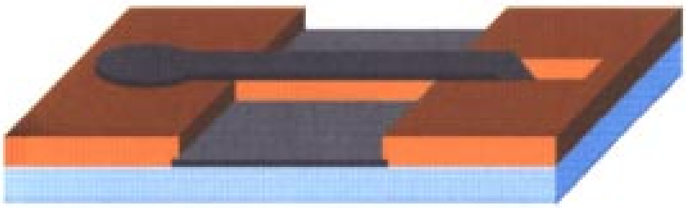


Figure 36 : Schematic of the MGC design pursued at IMEC.

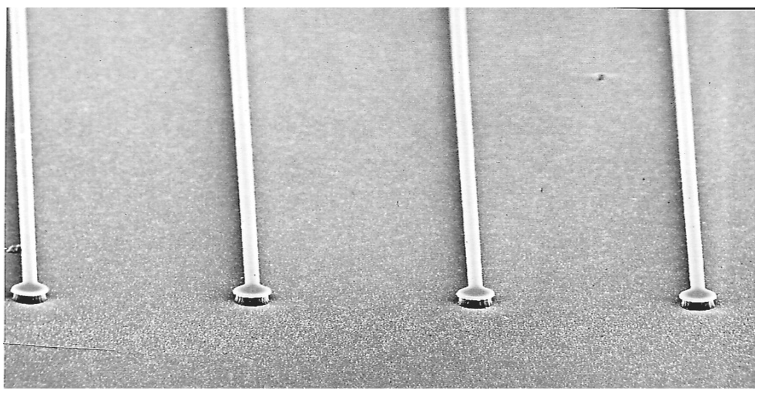


Figure 37 : Scanning Electron Microscope picture of an MGC structure produced at IMEC.

(*) VITO : Vlaams Instituut voor Technologisch Onderzoek, Mol, Belgium
(**) SRON : Space Research Organisation Netherlands, Utrecht, Netherlands
(***) IMEC : Interuniversity Microelectronics Centre, Leuven, Belgium

XI. SIMULATION STUDIES

An important aspect of any layout of the tracker resides in the material budget it represents in front of the crystal electromagnetic calorimeter and the distribution of this material. The entire layout of the design presented here, based on 14 wheels on either side of the barrel, has been introduced into CMSIM. All construction parts and materials have been taken into account ie :

- The dodecagonal support structure
- The composite bottom panel of the banana boxes
- The integrated gas input and output manifolds
- The integrated cooling pipe filled with water
- The substrates and drift planes
- The equipped readout and HV hybrids
- The cover foil of the banana box
- The substrate fixation excentrics

The following simplifications have been introduced into the code :

- The dodecagonal polygones of the support structure have been approximated by circles
- The material of the readout and control chips has been smeared out over the sur face of the hybrid
- The inter-banana radial edges (peek or vectra U profiles of 1 mm thickness) have been omitted so far.

Photons emitted at the interaction point, with a constant rapidity distribution, have been simulated. The resultant material budget, in terms of radiation length versus rapidity, for the 14 forward wheels is shown in figure 38. Electrical cables and optical fibres are not yet included as these services are essentially independent of the particular mechanical design and layout. It needs to be stressed however that all the gas and cooling pipes on the wheels are included in this simulation. A visual presentation of the x, y coordinates of γ conversion points is shown in figure 39 for 1.7 10^6 photons traversing a single forward MSGC wheel, situated at Z = 125 cm. This tool will allow for a quick comparison between different designs and layouts.

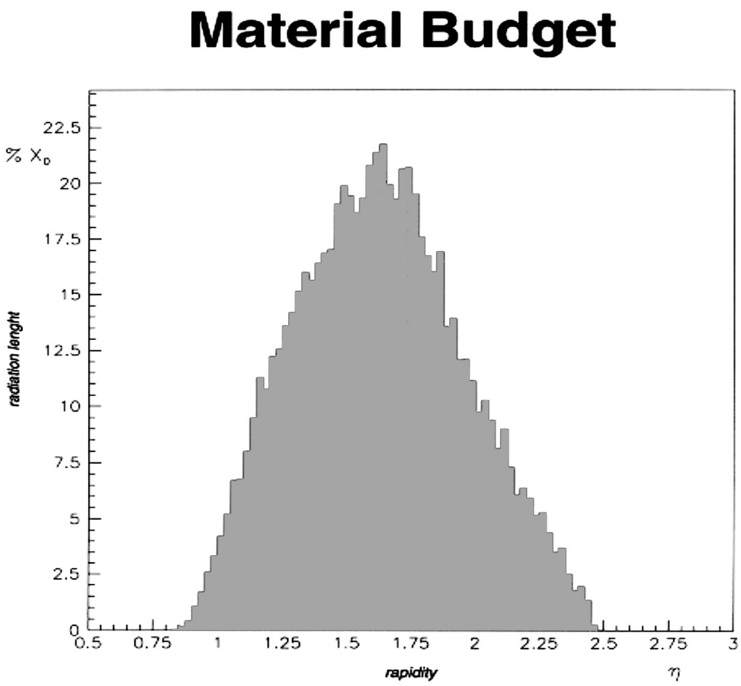


Figure 38 : The material budget, in terms of radiation lengths, for the 14 fully equipped forward MSGC wheels as a function of rapidity.

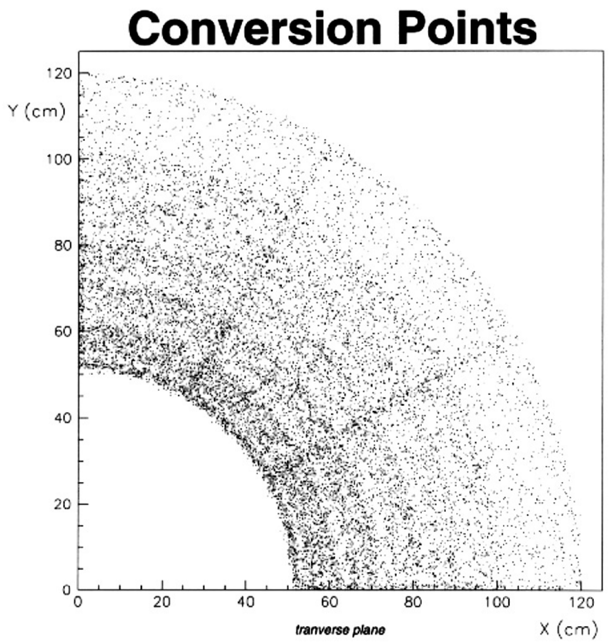


Figure 39 : Distribution of γ conversion points for a single forward MSGC wheel (one quarter shown).

XII. BUDGET AND MANPOWER REQUIREMENTS

The design presented in this report consists of 28 forward-backward MSGC wheels, each of which supports 296 individual detectors assembled into 36 banana boxes. Every detector substrate contains 512 anode strips yielding a total of 4.25 10^6 channels. For the stereo measurement (1 out of 2) a double read out pitch is assumed adding 1.05 10^6 channels. The main cost driving items are undoubtedly the unit price per read out channel and the cost of MSGC and MGC substrates. Following the estimate of the CMS costbook (version 7), a unit price per read out channel of 2.4 CHF is taken. In the costbook the price assumed for an MSGC substrate is 325 CHF whereas an MGC substrate is costed 1000 CHF. These items alone therefore add up to 0.6 MCHF per forward wheel equipped with MSGC's and to 0.85 MCHF for a MGC wheel. Adding the costbook estimates for front end hybrids (57 CHF/u), HV hybrids (12 CHF/u) and drift planes (50 CHF/u) yields a total price for the detectors alone of one forward wheel amounting to :

MSGC FW wheel : **0.64** MCHF
MGC FW wheel : **0.89** MCHF

Since it is of general belief that a substantial reduction of the price per channel for the front end electronics is very unlikely, two possibilities remain to reduce this cost; reducing the number of channels and/or reducing the price per substrate. The number of channels can be reduced by limiting the acceptance (e.g. no inner ring), increasing the pitch of the anodes or reducing the number of wheels. All these possibilities need to be confronted with the simulations to check whether the physics performance remains acceptable[(*)].

The second approach i.e. reducing the price per substrate is actively pursued within our community. With all the possible producers of substrates (VITO, IMEC, SRON) we investigate the possibility to run the mass production with existing institute manpower. Considering furthermore that all these potential producers are government subsidised research plants, not required to make a benefit, a target price 40% below the cost book estimate is aimed for. Using such an approach at SRON, the price paid by NIKHEF for a large area HERMES MSGC (512 channels, aluminium metalisation, no coating, resistors included in the artwork) was 100 CHF. This was only possible by putting a skilled technician in the plant during production.

For the cost of the mechanics of the 28 forward wheels produced in the way presented in this paper, firm price offers exist for many of the components. They are summarised below :

Composite C fiber panels	500 CHF/m^2	126 kCHF
cutting panels into bananas		160 kCHF
C fiber struts for support structure	24 CHF/m	20 kCHF
Thin wall alu tubes	10 CHF/m	28 kCHF
Laser drilling of holes		10 kCHF

yielding a total, for the 28 wheels, of 344 kCHF. Components which are uncosted so far are :

- U shaped side profiles (vectra or peek)
- Alignment pins (peek)
- Fixation pieces and excentrics (peek)
- Gas and water input/output pieces (vectra or peek)
- Aluminised kapton foil
- C fiber assembly pieces for the support structure

Many of these parts could be produced in workshops belonging to the participating institutes. It is believed that a conservative and safe estimate for the forward wheel mechanics presented in this report amounts to :

[(*)] In the new baseline layout presently under investigation only 2 x 10 forward wheels are envisaged with a decreased acceptance (only 5 detector rings) per wheel.

FW wheel mechanics : **25** kCHF/wheel

This is substantially less than the provision made in the costbook due to the simplicity of the design.

A first estimate of the required manpower can be obtained from the construction of the HERMES MSGC system performed at NIKHEF. Averaged over the 52 counters of this system, 2 man days/detector were required, including manual bondings and all the testing procedures outlined in section VI. On average a fully equipped and tested banana is therefore expected to require about 20 man days. The entire forward MSGC system of CMS consists of 1008 such banana boxes. At present the forward MSGC community envisages a distributed construction scheme with 3-4 regional centers (e.g. Belgium, Germany, France, Russia ?). The amount of bananas to be produced per center ranges between 280-350 including spares. Considering a 5 year production period, a throughput of maximum 70 bananas/year is required translating to 2 bananas/week. A team of 8 well trained technicians per regional center could handle this mass production. Clearly, manpower for the production of substrates and mechanical parts is not included in this estimate.

CONCLUSIONS

This report presents a summarised compilation of the design work, calculations and measurements carried out to reach a possible approach for the construction of the CMS forward-backward MSGC tracker. Its pretension is not to be a complete prescription of how to meet all the challenges that this ambitious and complex project raises, but rather to provide indications and experimental proofs that the concept put forward here will lead to a detector meeting the requirements of CMS. A lot of work is still ahead, and the milestone prototype, due by summer 1997, has to serve the purpose of proving the validity of this approach in all aspects, before mass production can start.

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