R&D PROJECTS IN COLLABORATION WITH CERN

2000

TECHNICAL ANNEX

Collaboration in the CMS Experiment

"Development of the CMS Alignment System"

21 September 2000

"Development of the CMS Alignment System"

ABSTRACT

LIP is a member of Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) presently in preparation at CERN. The experiment aims at the study of very high-energy collisions of proton beams. Investigation of the most fundamental properties of matter, in particular the study of the nature of the electroweak symmetry breaking and the origin of mass, is the experiment scope. The design goals of CMS detector are the identification and precise measurement of muons, electrons and photons, with an energy resolution better then 1% at 100 GeV. This is achieved with a robust and redundant muon system, the best possible electromagnetic calorimeter and a high quality central tracker. The central Tracking System and the Muon System will play a major role in all physics searches of the Compact Muon Solenoid experiment at LHC and their performance depends upon their intrinsic detector characteristics, on the stability of the supporting structures and on the overall position monitoring and alignment system.

The performance of the Position Monitoring System, PMS, of the Tracker the Muon System, strongly depends on the stability and performance of Composite Structures. These large structures must be light, highly stable, stiff and radiation tolerant in an environment where external vibrations, high radiation levels, material aging, temperature and humidity gradients are not negligible. In the Tracker there are two of these structures made of Carbon Fibre composite sandwich material. For the Muon position monitoring system there are 36 structures each made of Carbon Fibre composite tubes connected together in a complicated network with overall dimensions of 4x1 m^2. One prototype of the tracker structure, manufactured by one of the participating institutes, will be studied for mechanical stability when subjected to static loads (cross checking of finite element model). At present we are completing its dynamic characterisation. Engineering studies aiming at full manufacturing specifications started already on the Muon structures. Given their complexity and diversity, we propose to concentrate most of our efforts in this work.

As mentioned before, vibrations of these structures can seriously compromise their performance. Therefore we propose to continue the successful R&D on shape and dynamic control of composite structures using piezoelectric sensors and actuators. This is a very active subject in the area of the "so called" Smart Structures with a large spectrum of applications beyond the one we are working on.

In CMS Tracker some silicon detectors are used to detect particles and the Nd-YAG laser light from the PMS. These detectors are slightly modified ones where a small hole is etched in the Aluminium backplane. Optimisation of the optical transmission might lead to a deposit of anti-reflective coatings on the hole. Optical and electrical characterisation of these detectors will be done in order to evaluate any possible changes of their performance. Also the influence of exposure to intense Nd-YAG laser light will be studied.

The work will be divided into the following tasks:

- *Track Finding and Track fitting techniques applied to CMS Alignment*
- *Final studies and prototype of the Tracker structure*
- *Study of the Glass Fibre prototype of the Muon Alignment Structure.*
- *Construction of 2 carbon fibre prototypes of the Muon Alignment Structure.*
- *Tests of the mechanical properties of the prototypes and tunning of the models.*
- *Definition of the manufacturing procedure for the composite structures of the CMS alignment system.*
- *R&D on the active control of vibrations of composite structures using piezoelectric sensors and actuators.*
- *Study of the performance of the modified Silicon detectors.*
- *Definition of the etching and anti-reflective coating manufacturing procedure.*

"Desenvolvimento do Sistema de Alinhamento de CMS"

RESUMO DO PROJECTO

O LIP é membro da colaboração CMS (Compact Muon Solenoid) do acelerador LHC (Large Hadron Collider), actualmente em preparação no CERN. Esta colaboração tem como objectivos o estudo de colisões de feixes de protões de alta energia. A investigação das propriedades fundamentais da matéria, em particular o estudo da quebra espontânea de simetria e a origem da massa, fazem parte do vasto espectro de estudos a efectuar. Um sistema de detecção de muões robusto é fundamental para atingir estes objectivos. Em CMS, a trajectória dos muões é registada pelo detector de Traços Central e pelo Detector de Muões. O desempenho destes detectores depende da resolução intrínseca dos seus componentes, da estabilidade das suas estruturas e do sistema global de controlo de estabilidade e alinhamento.

O desempenho do sistema monitor da posição (*Position Monitoring System – PMS*), ou alinhamento, do Tracker e do Sistema de Muões, depende da estabilidade e desempenho de estruturas feitas de materiais compósitos de fibra de carbono *(Carbon-Fibre reinforced composite)*. Estas grandes estruturas devem ser leves, estáveis, rígidas e tolerantes à radiação num ambiente onde as vibrações induzidas, os elevados níveis de radiação, o envelhecimento do material e os gradientes de temperatura e humidade não são desprezáveis. No Tracker há duas destas estruturas feitas em sanduíche de Fibra de Carbono e Alumínio ou *Nomex*. No sistema de alinhamento do sistema de Muões, existem 36 estruturas semelhantes construídas em tubos compósitos de Fibra de Carbono ligados numa complicada teia com dimensões globais de 4x1 m^2. Um protótipo das estruturas do Tracker, construído por um dos Institutos participantes, será objecto de estudos de estabilidade quando submetido a cargas estáticas com o objectivo de afinar o modelo de elementos finitos. Esta estrutura encontra-se presentemente em fase final de caracterização dinâmica. Estudos de engenharia com o objectivo de definir os processos de fabrico das estruturas de alinhamento do sistema de Muões, encontram-se na sua fase inicial. Devido à sua importância, complexidade e diversidade, vamos concentrar grande parte dos nossos esforços no estudo destas estruturas.

Como foi mencionado anteriormente, as vibrações podem comprometer seriamente o desempenho destas estruturas delicadas. Dentro deste projecto canalizámos, com sucesso, algum esforço de R&D numa área de investigação emergente que é a do controlo activo de vibrações usando actuadores e sensores piezoeléctricos embebidos neste tipo de estruturas. Propomo-nos a continuar a investir este ano nesta nova área de I&D onde, depois de termos finalizado os estudos no controlo de forma, vamos abordar o controlo dinâmico.

No Tracker de CMS alguns dos detectores de silício são utilizados para detectar partículas e a luz proveniente de um laser de Nd-YAG. Estes detectores são ligeiramente modificados e um pequeno buraco é aberto no alumínio da parte traseira. A optimização da transmissão óptica, para este comprimento de onda, pode obrigar ao depósito de uma camada anti-reflectora nesta zona. A caracterização óptica e eléctrica destes detectores vai ser efectuada para detectar eventuais alterações no seu desempenho. Os efeitos da exposição ao feixe intenso de luz do laser de Nd-YAG vão ser estudados.

O trabalho encontra-se dividido nas seguintes fases:

- *Estudo de métodos de alinhamento com partículas.*
- *Estudos finais e protótipo "final" da estrutura do sistema de alinhamento do Tracker.*
- *Estudo do protótipo em Fibra de Vidro de uma estrutura do alinhamento do sistema de Muões.*
- *Construção de 2 protótipos em fibra de carbono de uma estrutura do alinhamento do sistema de Muões.*
- *Testes e determinação das propriedades mecânicas dos protótipos e ajuste dos modelos.*
- *Definição dos métodos de fabrico das estruturas compósitos do sistema de alinhamento de CMS.*
- *R&D em controlo activo de vibrações de estruturas em material compósito usando actuadores e sensores piezoeléctricos.*
- *Estudo das propriedades e desempenho dos detectores de silício modificados.*
- *Definição dos processos de modificação dos detectores de silício.*

“*Development of the CMS Central Alignment System*”

DESCRIPTION OF THE PROJECT

Introduction

The Compact Muon Solenoid experiment, CMS, is one of the two general purpose experiments foreseen to operate at the Large Hadron Collider, LHC, at CERN.

The CMS detector has been optimised for the search of SM Higgs boson over a mass ranging from 90 GeV, about the highest attainable value at LEP, up to 1 TeV. It also allows the detection of a wide range of possible signatures of alternative of symmetry breaking mechanisms and the study of CP violation, top, beauty, tau and heavy ion physics.

The design goals of CMS detector are the identification and precise measurement of muons, electrons and photons with an energy resolution better then 1% at 100 GeV. This is achieved with a robust and redundant muon system, the best possible electromagnetic calorimeter and a high quality central tracker.

The central Tracking System and the Muon System will play a major role in all physics searches of the Compact Muon Solenoid experiment at LHC and their performance depends upon their intrinsic detector characteristics, on the stability of the supporting structures and on the overall position monitoring and alignment system.

The performance of the Position Monitoring System, PMS, for the Tracker and for the Muon Systems strongly depends on the stability and performance of big Carbon Fibre Composite Structures (CFCS) that are the key of the geodetic network for each of the PMS. These large structures must be light, highly stable, stiff and radiation tolerant in an environment where external vibrations, high radiation levels, material aging, temperature and humidity gradients are not negligible. A careful choice of a Carbon Fibre Reinforced Plastic as structural material and a thorough engineering design can minimise the impact of these effects on the behaviour of the structures. Nevertheless, unforeseen factors and the unknown result of the coupling of environmental conditions, together with external vibrations, may affect the position stability of the structures, thus compromising their performance in the respective PMS.

In the Tracker there are two CFCS which made of Carbon Fibre composite sandwich structure. For the Muon position monitoring system there are 36 structures each made of Carbon Fibre composite tubes connected together in a complicated network with overall dimensions of 4x1 m^2.

One prototype of the tracker structure, manufactured by one of the participating institutes (Fig. 2), will be studied for mechanical stability when subjected to static loads to fine tunning of finite element model. At present we are completing its dynamic characterisation. Engineering studies aiming at full manufacturing specifications started already on the Muon structures. Given their complexity and diversity, we propose to concentrate most of our efforts in this work.

As mentioned before, vibrations of these structures can seriously compromise the performance of the PMS structures. Therefore we propose to continue the successful R&D on shape and dynamic control of composite structures using piezoelectric sensors and actuators. This is a very active subject in the area of the “so called” Smart Structures with a large spectrum of applications beyond the one we are working on.

In CMS Tracker some silicon detectors are used to detect particles and the Nd-YAG laser light from the PMS. These detectors are slightly modified ones where a small hole is etched in the Aluminium back-plane. Optimisation of the optical transmission might lead to a deposit of anti-reflective coatings on the hole. Optical and electrical characterisation of these detectors will be done in order to evaluate any possible changes of their performance. Also the influence of exposure to intense Nd-YAG laser light will be studied.

1. The Position Monitoring System of the CMS tracker and the Alignment Wheels

Recently, due to a modification on the tracker layout, the proposed PMS was modified in order to reduce the space required and to minimise, with the new layout, its cost/performance ratio. The proposed PMS is schematically shown in Figure 1.

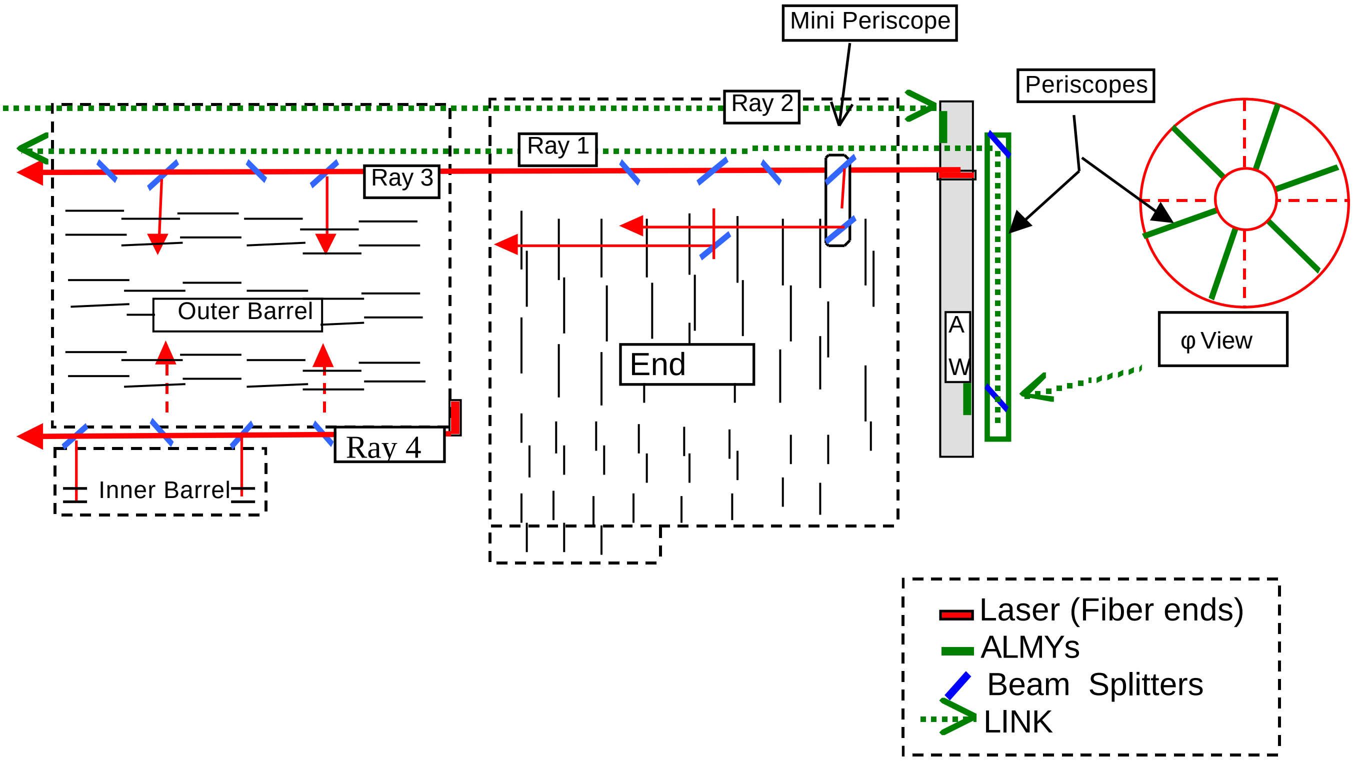


Fig. 1: Schematic view of the Tracker Position Monitoring System.

This system is based on the parallelism of coaxial light axis and on the accurate knowledge of the position and stability of their endpoints. These axis are collimated light beams coaxial with the Tracker cylinder at the outer Silicon detectors. Along its trajectory from one end of the tracker to the other, each light beam (Nd-YAG) will find beam-splitters and shine through several Silicon detectors. These detectors are part of the tracker detector elements and are able to efficiently detect event particles and light from the Position Monitoring System. For this purpose, these detectors must be modified by etching a hole on the Aluminium back-plane and by the deposit of an anti-reflective coating at the same place.

At both ends of the Tracker cylinder we will have two identical and highly stable structures that hold and define the orientation of collimated light beams. These structures are known as *alignment wheels* (Figure 2) and provide the connection between the tracker super-modules, and are also used to transport the Tracker coordinates into the Muon alignment via the Link system. The final dimensions of these alignment wheels are still to be defined; however we are working with the most unfavourable situation of the biggest possible dimensions.

A good performance of the alignment wheel, in terms of precision and stability, is directly dependent on the properties of the chosen materials and on the environmental conditions. The main parameters leading to the choice of material are the product of the Young's Modulus and the radiation length, the CTE and the CME. With the stringent design requirements for the alignment wheel, the choice is naturally oriented towards a CFRP, with a highly performing fibre and a resin qualified for aerospace applications (new generation of epoxy, or cyanate ester).

Fig. 2 - Prototype of the alignment wheel at INEGI

We have built a full-scale prototype of one alignment wheel (Figure 2). This prototype was modelled and a finite element analysis (ANSYS 5.4) has been performed to evaluate its mechanical stability.

From this prototype, once statically and dynamically characterised, one is able to validate the simulation models and a last iteration of the prototype should be build, as we are proposing, with the final, more expensive, material choice. If correctly done, this prototype could become the first of the two final wheels needed for the Tracker PMS.

The dynamic characterisation was done on the prototype with the minimum number of elements. The measurements showed a first natural frequency close to 13 Hz. The values obtained for the natural frequencies are presently used to tune the Finite Element model. This model will be further tuned with the results obtained from the static load measurements.

2. The Position Monitoring System of the CMS Barrel Muon chambers

Stability of the muon chambers at the 100 μm level is not guaranteed during detector operation. The expected movements and deflections of the muon spectrometer will exceed the requirements. To cope with movements, the detector is instrumented with an optical alignment system, which will allow continual measurement of the chambers position. The alignment information will be used as off-line correction for track reconstruction.

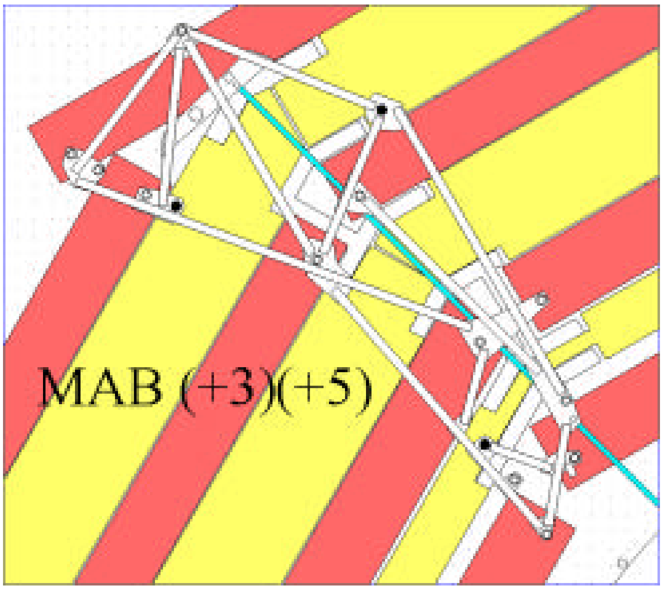
The position monitoring system for the barrel part is designed to measure the positions of the barrel chambers with respect to each other (internal monitoring). The position of the whole barrel muon system is related to that of the Central Tracker and the Endcap muon system via the Link system.

The full barrel system is segmented in six φ planes (*active alignment planes*) to which the three tracking detectors are connected. The range of movements to be monitored, and therefore the tolerances of the optical paths and dynamic range of the alignment elements, is mainly determined by the deflections produced when the magnet is turned on. During assembly, survey measurements based on photogrammetry techniques can provide accurate knowledge of the actual positions of the muon chambers and alignment components. Magnet tests foreseen during the installation period will provide information for detector position offsets. The survey measurements, and the possibility to adjust the key elements of the magnet yoke and alignment system, will allow the efficient use of the full range of the sensors and optical passages of the alignment system.

The scheme of the barrel position monitor system based on the monitoring of the muon chamber positions with respect to a network of 36 rigid mechanical reference structures called MABs (Module for Alignment of Barrel). The MABs are fixed to the barrel yoke forming 12 r-z planes parallel to the beam and distributed in φ. Six of them (called *active planes*) are connected to the link system. The other six planes (called *passive planes*) are connected to the active ones via diagonal connections.

The chambers are equipped with light sources on both sides. These light sources are mounted on frames rigidly attached to the chambers. Each of the 36 MABs contains 8 camera boxes, which observe these light sources mounted on the muon chambers. They also contain light sources and/or camera boxes for the diagonal connections, in addition, some are also equipped with cameras measuring the z positions by observing carbon-fibre bars called Z-bars installed on the vacuum tank of the CMS magnet. All the MABs that are connected to the link system contain also elements belonging to the link and endcap systems.

The MABs with all the elements mounted on them are considered to be rigid bodies with calibrated geometry having 6 degrees of freedom and are fundamental pieces of this Position Monitoring System. They are rigid structures made of carbon-fibre tubes and plates glued together. The MAB is fixed to the barrel yoke at three points in an isostatic way, allowing its movement without deformation. The rigidity is achieved by the construction, the choice of the material, and the assembly technology and stability at the 30 μm level is expected. In this proposal we aim at the construction of the first MAB prototype in Carbon Fibre to evaluate, in the first place, its static mechanical properties. This will provide an important check for the quality of the finite element model, which is, in this case, more difficult to match with reality given the uncertainties on the behaviour of all the gluing and connections of the different elements. Once we have the static properties in hand, we will proceed to the dynamic characterisation of the MAB, an important issue given the size of this structure.



Due to lack of rotational symmetry of the barrel muon system, the MABs have to be different. There is also a difference between the outer MABs connected to the link and endcap and the inner ones. A typical MAB layout is shown in Figure 3.

Other important components of this system are the camera boxes, light holder's etc. A full description of the system and its components can be found in the Muon TRD.

Fig. 3 - Layout of a MAB structure.

One of the problems with the present layout of these structures is the connection between the different elements. In order to study the behaviour of these nodes, we built a FibreGlass structure with a shape that includes all the types of connections of the final structure (Figure 4). This structure was subjected to static loads and the results obtained are now under study.

Fig. 4 – Glass fibre structure used to study the connections of the MAB.

From the results of this study we will build a full-scale prototype in Glass Fibre and we will measure its mechanical properties. Then we propose to build two prototypes with the final, expensive, carbon fibre material. Understanding the performance of these prototypes is the main subject of our work for the next year.

3. Active control of vibrations in composite structures

As mentioned before, vibrations may affect considerably the performance of the support structures. The suppression can be achieved by the use of a smart structure - basically it consists on a mechanical structure with sensors and actuators embedded in it. One of the most popular materials for sensors/actuators is the piezoceramics due to their high strength and to the easy of handle. A smart structure allows not only the damping of vibrations but it also permits its shape control. Up to now we proved that we could effectively dump the first natural mode of a small cantilever composite beam. The main objective will be to extend this work to more complex structures such as the ones of the alignment systems.

The shape control in one and two directions was achieved recently. The methodology used is a new one, based on the use of genetic algorithms to find the best location of piezoelectric actuators and the appropriate voltage set to achieve the pre-defined shape of a Aluminium beam and a Aluminium plate. Figure 5 shows the excellent agreement between the desired shape, the expected results from the Finite Element model and the measured shape.

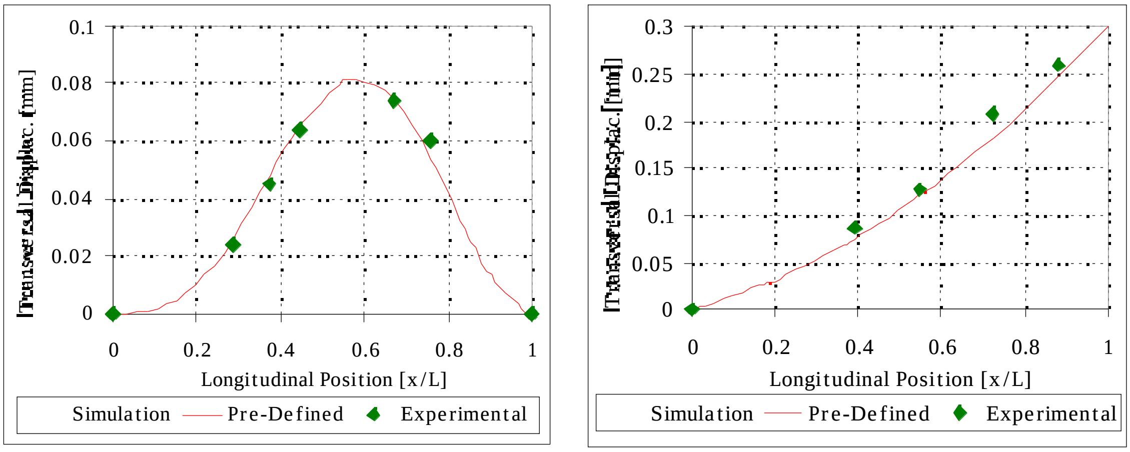


Fig. 5 – Fig. 2 Comparison between the pre-defined displacement field, simulation results and experimental measurements for the clamped-clamped beam (left) and, for the clamped-free plate with a thickness of y=0.012mm (right).

We propose to pursue this work with the study of optimal placement of sensors and actuators using a genetic algorithm approach and the use of modern control methodologies applied to vibration control of complex structures.

4. Aim and Objectives of the project

We are now sure to have found the correct partners and working environment to allow the successful development and manufacturing of the delicate Composite structures of the CMS alignment systems.

The engineering studies done for the Tracker Alignment Wheel will be completed during this year's project. In this project we propose to fine tune the FE models wit the results from the dynamic and static measurements. Then, with these results we will build a final prototype that can become one of the final wheels to be used in CMS. This structure will be build with the final, much more expensive, material, leading to an effective increase of the prototype cost.

The experience and competence acquired with the alignment wheel structures is being applied to the more complex structures of the Muon alignment structures. This knowledge together with the results obtained with the Glass Fibre structure will be used to manufacture one full-scale prototype in low-cost Carbon Fibre. After its mechanical characterisation and tunning of the models, we propose to build a prototype with the final material and to write the specifications for manufacturing. This will naturally lead us to be a strong candidate for the construction of these delicate structures, certifying our institutes for further international commitments on this hightech area.

During the last year we proved that the use of piezoelectric actuators and genetic algorithms to optimise their position and voltages is a successful approach for the shape control of mechanical structures. With our previous experience on vibration control on a cantilever beam we propose to extend this methodology to optimal placement of piezoelectric sensors and actuators for active vibration control of complex structures. This is the subject of an innovative PhD work on this active field.

We have been involved up to now on the engineering work of the Composite structures for the CMS alignment systems. This year we propose to enlarge, with modest costs, the scope of our participation on the project to the characterisation of the optically modified silicon detectors. LIP-Algarve (at the University of Faro) in collaboration with Optics Labs (Pakistan) will do this work. We propose to study the performance of CMS silicon detectors after each step on their modification; Aluminium etching and anti-reflective coating. Also the influence of exposure to intense Nd-YAG laser light will be studied. For this we will use the entire infrastructure and expertise existing at these institutes.

4. Plan of the Work

Several activities will be carried out throughout the one-year duration of the Project:

TASK 0 – Track Finding and Track fitting techniques applied to CMS Alignment
Participants: LIP/CERN
Deliverable: Report

TASK 1:- Final studies and prototype of the Tracker structure
Participants: INEGI/FEUP/LIP/CERN
Deliverable: Report and prototype

TASK 2:- Study of the Glass Fibre prototype of the Muon Alignment Structure.
Participants: INEGI/FEUP
Deliverable: Report

TASK 3:- Construction of 2 carbon fibre prototypes of the Muon Alignment Structure
Participants: INEGI
Deliverable: Prototype

TASK 4:- Tests of the mechanical properties of the prototypes and tunning of the models.
Participants: INEGI/FEUP/CERN
Deliverable: Report

TASK 5:- Definition of the manufacturing procedure for the composite structures of the CMS alignment system.
Participants: INEGI/FEUP/CERN
Deliverable: Report

TASK 6:- R&D on the active control of vibrations of composite structures using piezoelectric sensors and actuators

Participants: FEUP/LIP/CERN
Deliverable: Report

TASK 7:- Study of the performance of the modified Silicon detectors.
Participants: CERN/Optics Labs./LIP-Algarve
Deliverable: Report

TASK 8:- Definition of the etching and anti-reflective coating manufacturing procedure.
Participants: CERN/Optics Labs./LIP-Algarve
Deliverable: Report

5. Time Schedule

TASK	*MONTH*											
	1	2	3	4	5	6	7	8	9	10	11	12
0	■	■	■	■	■	■	■	■	■	■	■	■
1	■	■	■	■	■	■	■	■	■	■		
2	■	■	■									
3		■	■	■	■	■						
4					■	■	■	■	■	■	■	
5											■	■
6	■	■	■	■	■	■	■	■	■	■	■	■
7	■	■	■	■	■	■	■	■	■	■		
8											■	■

4. Available and Necessary Resources

Available Equipment relevant for the project:

∝Double cavity YAG Laser *(180mJ/impuls).*
∝Several Ion CW lasers*(5mW-5W)*.
∝3 optical tables *(NRC).*
∝Holograph camera.
∝Micrometer positioners*(0.1mm-1mm MicroControl)*.
∝Acoustic modulators.
∝Several CCD cameras
∝ *digital lock-in amplifier,*
∝Digital oscilloscope (spectral analyser, wave form, etc..)
∝Dynamic data acquisition system
∝Electric extensometry system
∝2 workstations HP- 700
∝Other optical equipment
∝Several image processing plates for PC and WS
∝ Image processing and finite element software
· 2 4-point bending fatigue machines with imposed displacement
· Static universal testing machine 300kN
· Oven UTS 70 (0-200^{o} C)
· Nicolet NIC 310 oscilloscope
· Vacuum pump
· Acoustic emission LOCAN 320
· DMTA
· Hounsfield tensometer
· Polimer Laboratories cone calorimeter
· HDT / VICAT
· Internal pressure testing machine, up to 300 bar static or 150 bar cyclic
· 6 4-point bending creep testing machines
· 2 tension creep tension machines
· 2 workstations 1 HP- 700 and 1 DEC 5125
· Finite element software (IDEAS,ABAQUS,ADINA, IN-House)
· Autoclave 300 C, 15 bar pressure, 900mbar vacuum
· Filament winding machine, 6 CNC axes, 3 m long, 0.5m diameter
· Hot plate press, 400C, 300mm x 300mm
· Repair portable equipment for composite materials
· Instrumented Rosand impact machine
· Linear and angular measuring machines

· Computing facilities
· Mechanical and electronics workshops at CERN
· Mechanical and optical components at CERN and Optics Labs. (Pakistan)
· Silicon characterisation facility at the University of Faro

Equipment Required:

- Piezoelectric transducers
- Data acquisition system upgrading
- Impact Hammer

Extra Human Resources Required:

∝One ***Research Engineer*** to participate on the R&D of the prototypes.
∝One ***Senior Consultant***.

“Development of the Alignment System for the CMS Tracker”

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"Development of the Alignment System for the CMS Tracker"

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