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Proposal to Expand the Role of US CMS in the CMS Silicon Tracker Project: Impact on FNAL*

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Abstract

In December of 1999, CMS agreed to an alteration of the design of the tracker in which the microstrip gas chambers (MSGCs) would be replaced by additional single sided silicon microstrips. This decision, while reducing many of the technical risks that existed in the earlier design, increased the total surface area of silicon microstrips to roughly 230m^2 from under 100m^2. As a result, a major reorganization of the tracker project was required. The current plan includes an expansion of the US CMS role in the project to the production of 6600 single-sided outer barrel modules (~110 m^2) from 1000 single-sided inner barrel modules. We describe this proposal, its cost, expected schedule, and funding. The resources we will need at FNAL are also delineated. We discuss the likely interactions of this project with the CDF and DØ Run 2b Silicon upgrades. In spite of the large number of modules involved, the capacity requirements at SiDet are not excessive. With appropriate contingency planning, conflicts with FNAL projects can be avoided. This project can contribute positively to the Tevatron Collider programs by providing new technologies that facilitate the construction of Run 2 silicon replacements at lower costs. The cost of the project is $2.6M with an estimated $1.7M contingency. The project would have duration of approximately 3 years beginning this autumn.

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1. Overview

The US CMS Silicon tracker group was previously approved to build 1000 single-sided equivalent modules and associated shell supports cylinders for the inner two barrel layers of the CMS Silicon tracker. In December 1999 it was decided to remove the MSGCs from the design and to build instead an all-Silicon tracker. A provisional layout and production plan for the tracker was presented to the LHCC as an addendum to the tracker TDR in February[1] and was approved this May. In the interim, several modifications to the design were proposed and accepted by the CMS tracker group. In particular, a new layout was approved. The new layout no longer includes the cylinder that was previously intended to thermally separate the MSGCs from the Silicon. In addition, the previously separated inner and outer rings of the forward tracker have been merged. The forward system will now contain large all-silicon disks. The new layout is shown in Figure 1.

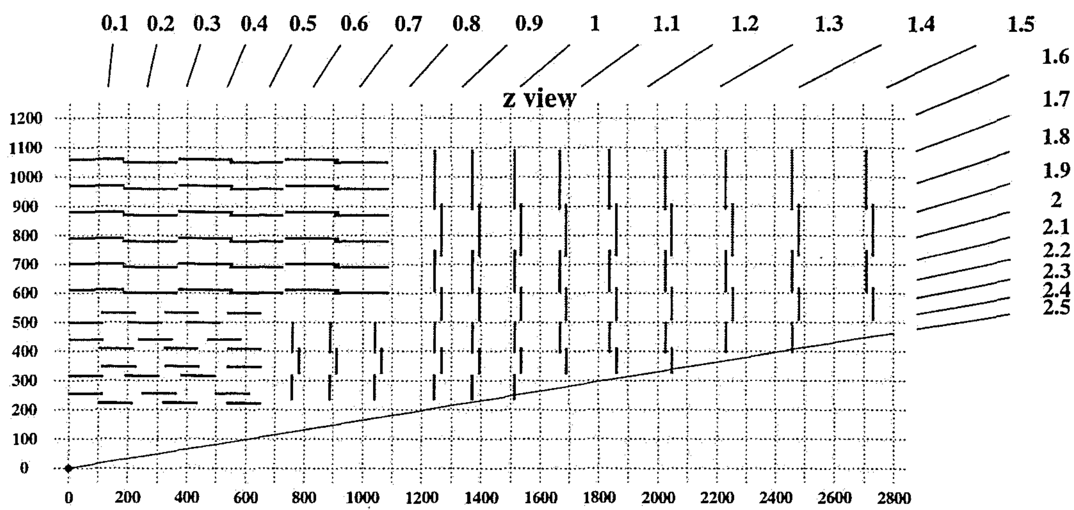

Figure 1. The CMS Silicon Tracker Layout. Barrel layers 1, 2, 5, 6, and 8 and forward disk rings 1, 2, and 5 will include 100 mrad stereo views. (Dimensions are in mm.)

In the CMS Silicon tracker, double-sided modules are everywhere constructed by stacking two single-sided modules back-to-back. Furthermore, the stereo side makes use of silicon with axial strips by turning the sensors 100 mrad relative to the beam axis. The same readout hybrid can be used on the stereo side by means of a wedge-shaped pitch adapter. To good approximation, one double-sided module is equal to two single-sided modules. The front-end readout for all modules is based on the analog APV chip[2], which has been fabricated in IBM 0.25 μm technology. The APV chip has been exposed to extremely high radiation doses with little subsequent degradation in performance. The Tracker is made up of the following sub-systems:

- Tracker Inner Barrel (TIB): Four cylindrical layers with 300 μm thick sensors. Modules are tilted 9° to compensate for Lorentz drift and installed in "shell" support mechanics. The two innermost layers are double-sided. The layout is summarized in Table 1.
- Tracker Outer Barrel (TOB): Six cylindrical layers with 500 μm thick sensors. Three layers are double-sided. The modules are installed in support rods that are mounted to end plates. The layout is summarized in Table 2.
- Tracker Small Disks (TSD): Three small end-cap disks are to be installed just beyond each end of the TIB. Each disk has 3 rings of modules with 300 μm thick sensors. The inner two rings are double-sided. The modules are installed into petal supports, which are wedge-shaped. Each petal has modules for all 3 rings and a full disk is made up of many petals. The layout is summarized in Table 3.
- Tracker End Caps (TEC): Nine end-cap disks are to be installed just beyond each end of the TOB and TSD. Each disk has 7 rings of modules. The modules in the inner 3 rings are identical to those in the TSC. The fourth ring also uses 300 μm thick sensors. The outer 3 rings use 500 μm thick sensors. Rings 1,2 and 5 are double-sided. The modules are again installed into petal supports, which are wedge-shaped. Each petal has modules for all 9 rings and a full disk is made up of many petals. The layout is summarized in Table 3.

For the construction of the newly designed tracker, the project was reorganized into 4 geographical consortia including a proposed USA consortium. The consortia and their respective responsibilities are as follows:

1. Central Europe (CE) – This consortium is made up mainly of what were previously MSGC institutes. The CE consortium is responsible for all forward disk modules. These are comprised of 8500 single-sided modules. The CE will install the modules on petal supports and later construct the petals into full disks.
2. CERN - The CERN consortium will take responsibility for overall integration, general support structures, cooling and inert gas flow, position monitoring and alignment. CERN will also be responsible for mechanics, cooling, and final assembly of the TOB.
3. INFN – The INFN consortium is responsible for the mechanical design of the TIB. INFN will construct all of the roughly 4000 TIB single-sided modules and most shell supports.
4. USA – The USA consortium is to be responsible for the production of all of the ~6600 single-sided TOB modules and their installation into support rods. The USA will also assemble the shell supports for two of the TIB layers.

Layer	Radius [mm]	Modules In φ	Total Modules	APV Chips	φ pitch [μm]	Stereo [μm]	Total APV's
1	239	28	336	6+6	80	80	4032
2	331	38	456	6+6	80	80	5472
3	423	46	552	4	120	-	2208
4	515	56	672	4	120	-	2688

Table 1 Tracker Inner Barrel (TIB) .

Layer	Radius [mm]	Modules In ϕ	Total Modules	APV Chips	ϕ pitch [μm]	Stereo [μm]	Total APV's
5	605	42	504	6+4	122	183	5040
6	695	48	576	6+4	122	183	5760
7	785	54	648	4	183	-	2592
8	875	60	720	4+4	183	183	5760
9	965	66	792	6	122	-	4752
10	1055	74	888	6	122	-	5328

Table 2 Tracker Outer Barrel (TOB)

Ring	Modules In ϕ	Rings in z	Total Modules	APV Chips	Pitches ϕ [μm]	Stereo [μm]	Total APV's
1	24	12	288	6+6	81/112	81/112	3456
2	24	18	432	6+6	113/143	113/143	5184
3	40	22	880	4	123/158	-	3520
4	56	18	1008	4	113/139	-	4032
5	40	18	720	6+6	126/156	126/156	8640
6	56	18	1008	4	163/205	-	4032
7	80	18	1440	4	140/172	-	5760

Table 3 Tracker End Cap (TEC) and Tracker Small Disks (TSD) first 3 layers.

The tracker as described, provides a large number of high resolution track hits as seen in Figure 2. The material budget corresponds to roughly 2% X_o per layer at normal incidence. This is comparable to what is currently expected for the CDF Run 2a SVXII detector.[3] The sub-system component counts are summarized in Table 4.

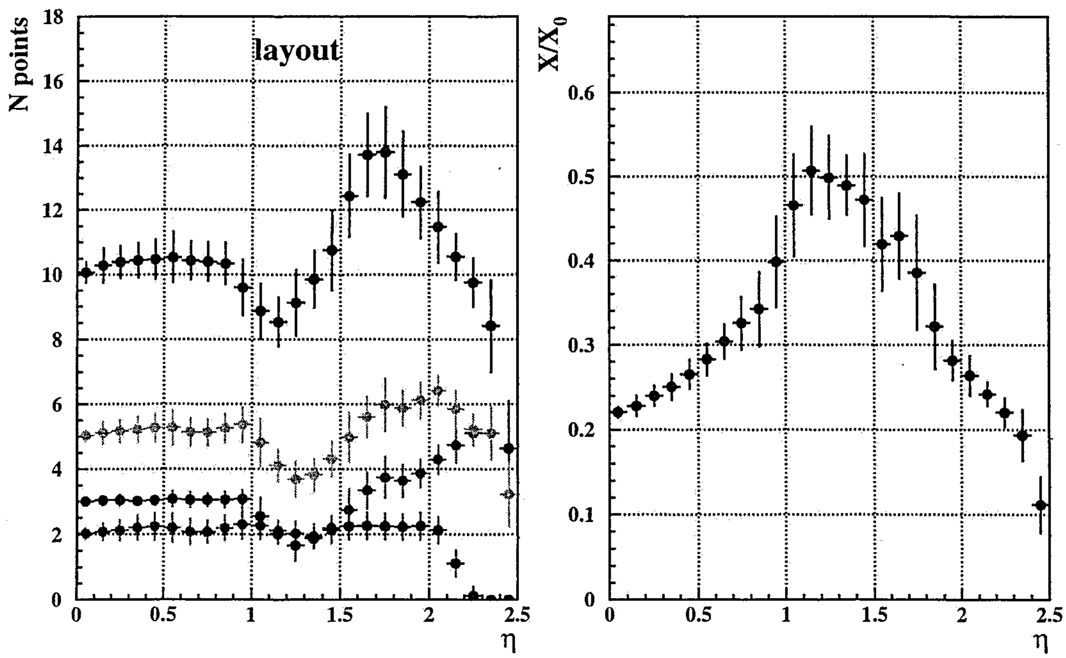

Figure 2 Tracking layers and material traversed by tracks as a function of pseudorapidity.

Sub-System	SS Modules	DS Modules	6" Wafers	APV Chips	Wirebond Wires
TIB	1224	792	2808	14400	5.5 M
TOB	2328	1800	11856	29232	11.2 M
TSD	1888	720			
TEC	3328	2448	11104	34624	13.3 M

Table 4 Summary of single-sided equivalent modules, wafers, chips and wirebond wires.

A draft of the tracker production schedule was presented during the CMS tracker week at CERN in April 2000. The project begins with a pre-production series of 200 modules, (80 TOB, 80 TEC, and 40 TIB modules). The pre-production will take place from November 2000 until some time in the summer of 2001. This exercise calls for the use of final production methods and as close to final components as possible. CERN has developed an automated module assembly process based on a pick-and-place gantry as seen in Figure 3. Efforts are underway to prepare all necessary components to service seven gantry systems, of which two would be purchased by the USA consortium.

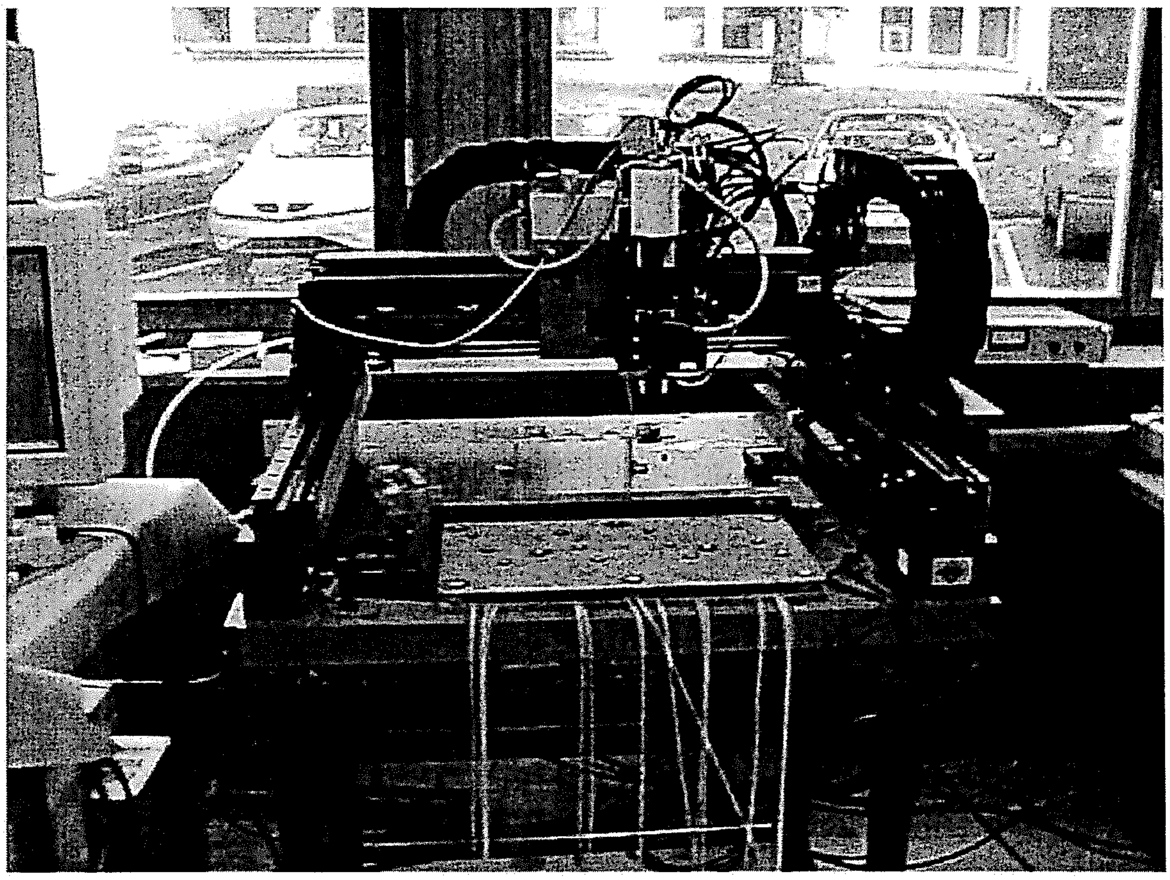

Figure 3. Pick-and-place gantry system developed by CERN for automated assembly of CMS Silicon modules.

The pre-production period would be followed by a production period from August 2001 until January 2004. The TOB, which would be the responsibility of the USA consortium, needs to be completed by Autumn of 2003 since the schedule calls for installation of all TOB rods by December 2003. As discussed in more detail below, this schedule is likely to overlap the FNAL Run 2b Silicon replacement production schedule.

2. The USA Consortium and the TOB Project

As discussed in the previous section, the US CMS Silicon tracker group is proposing to take responsibility for the production of Tracker Outer Barrel (TOB) modules and their installation into rods. This is a large effort, comprising 6000 installed and 600 spare modules with a Silicon surface area in excess of 100 m^2. This expansion of the role of the US CMS tracker group is partly necessitated by the decision to build an all-Silicon tracker. It would benefit all parties involved for a number of reasons. For instance, this project would expand the involvement and visibility of the US CMS collaboration in the central tracker, which is a key element of the physics capabilities of the detector. In addition, the US group, together with the technical manpower and equipment available at the FNAL Silicon Detector Center (SiDet), is arguably the most experienced and well-equiped production group in the project. We would therefore be able to provide a significant base for the overall effort. The hadron collider physics experience of the US group will also be important to the physics program of CMS.

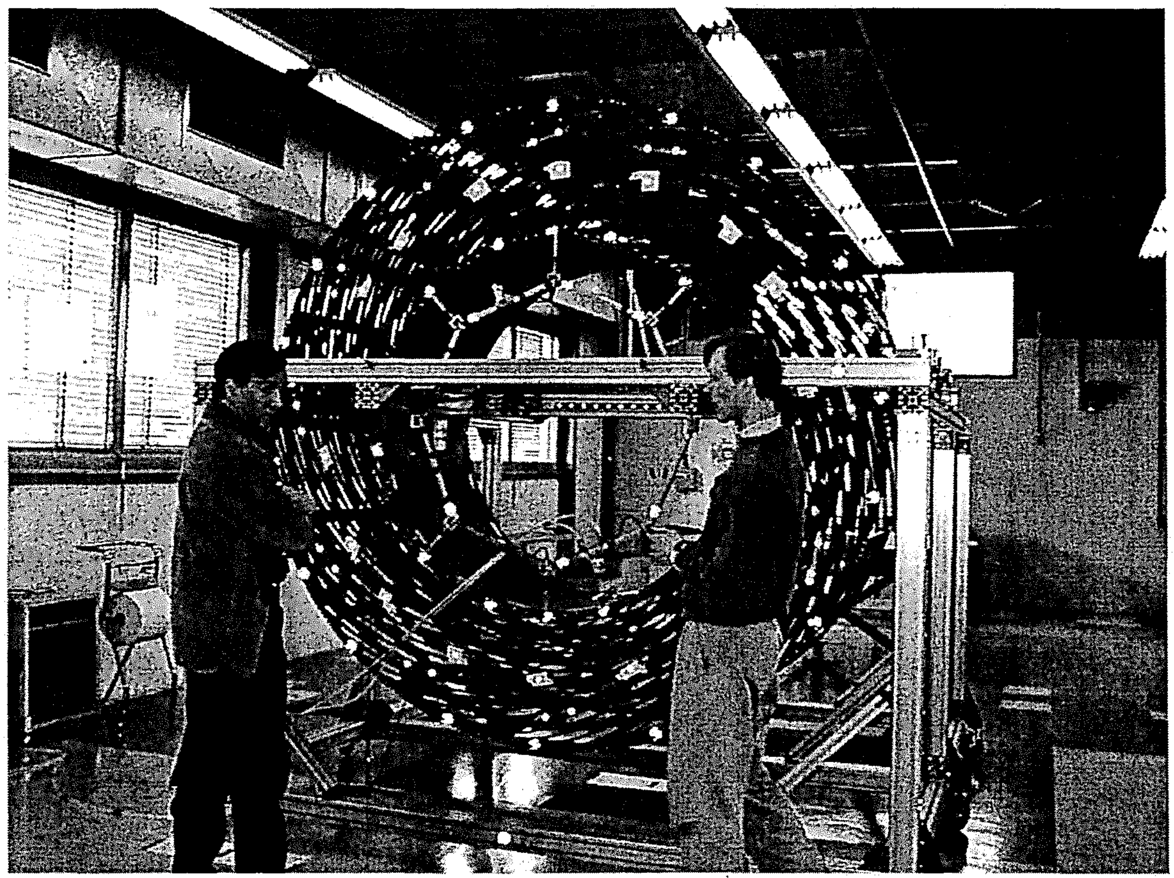

Figure 4. Prototype support structure at CERN for the TOB rods.

This effort will also provide positive spin-offs for FNAL. For instance, the importation of automated module assembly systems could enable low-cost and high rate module production for Run 2b Silicon replacements. The CMS experience in radiation tolerant Silicon and readout electronics for CMS has already influenced the Tevatron Collider in the design of the CDF Layer 00 Detector[4] and is having an ongoing impact on the planning for Run 2b. The CMS mechanical support and cooling system designs will also have a significant impact on the designs of Run 2b Silicon detectors.

A prototype support system for TOB rods is shown in Figure 4. The assembly drawing for module installation in rods is shown in Figure 5. A prototype of the protruded Carbon Fiber Rod support is shown in Figure 6.

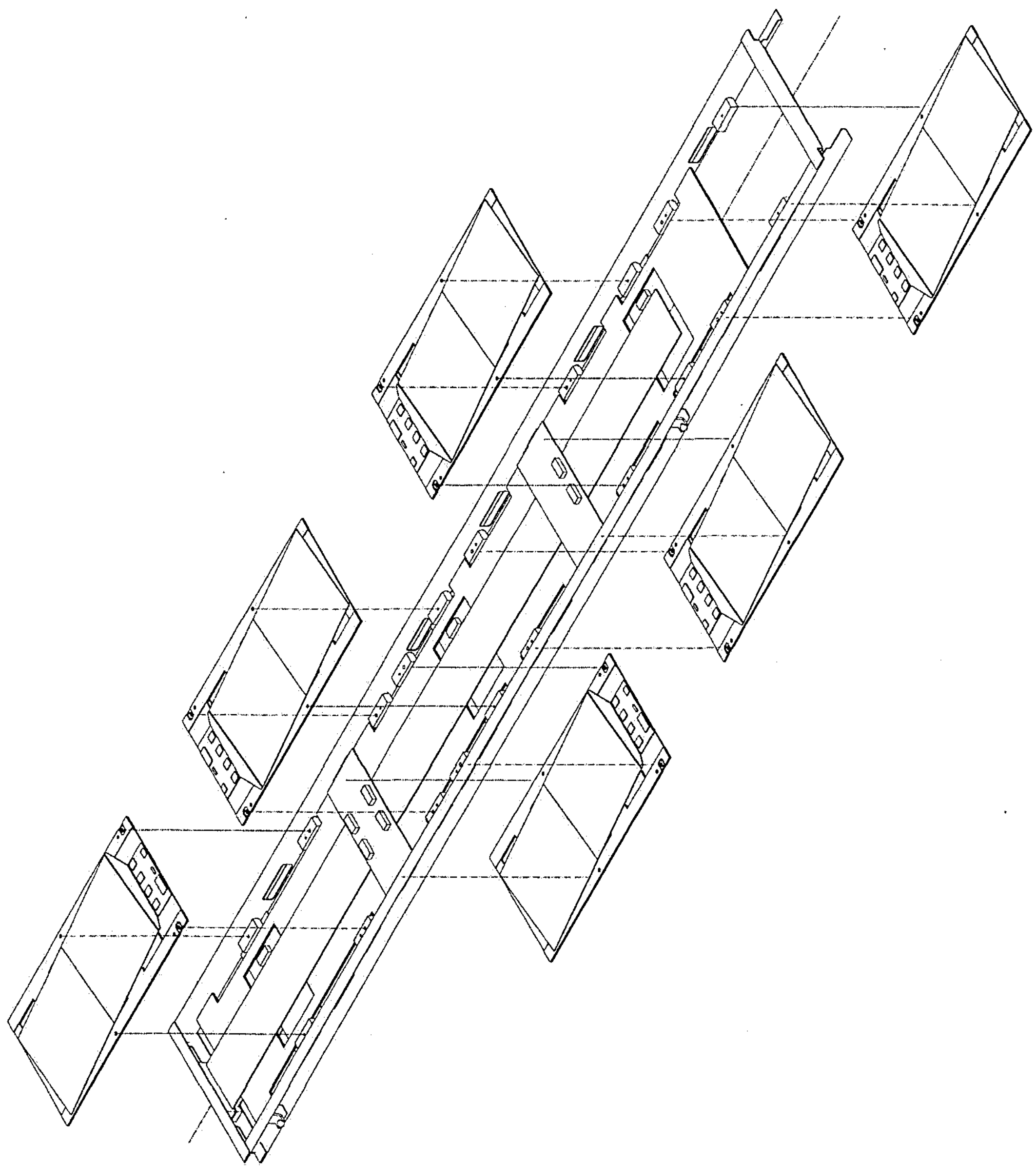

Figure 5. Assembly drawing for TOB rod.

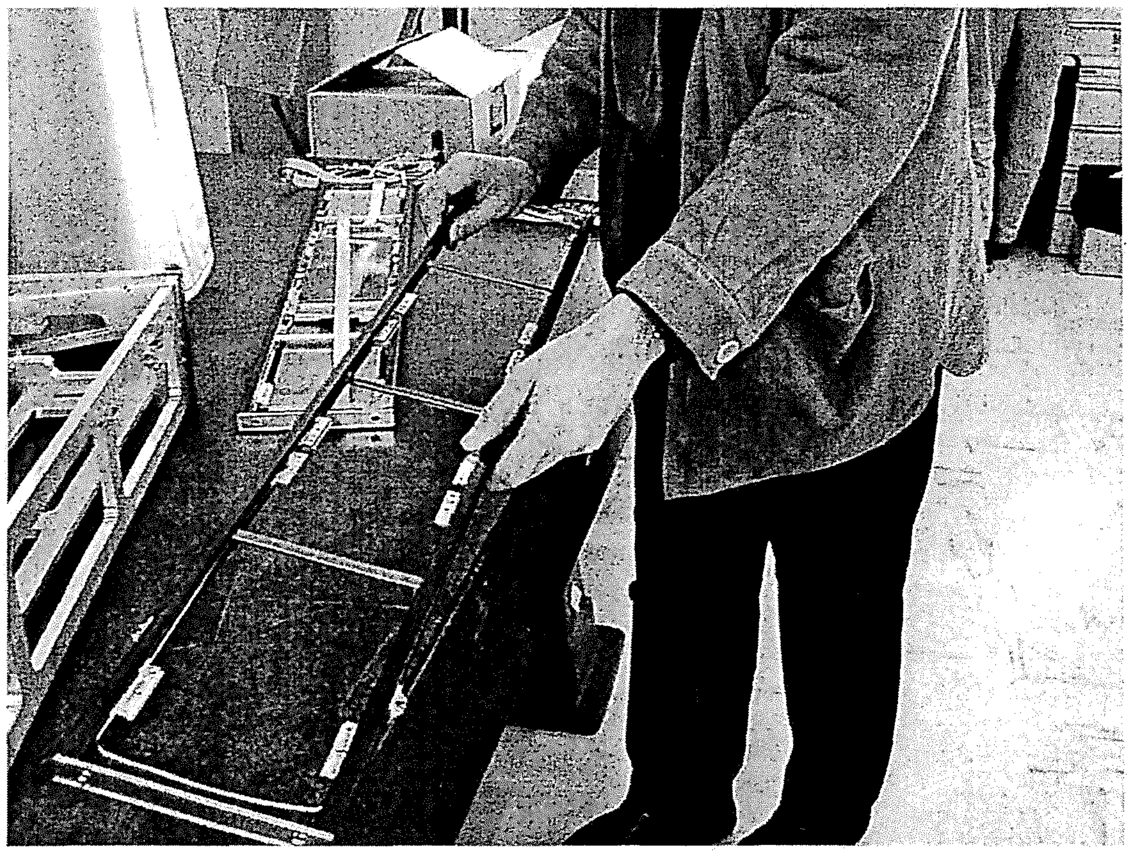

Figure 6. Protruded Carbon Fiber Rod support with cooling pipes.

The USA Consortium would plan to construct the TOB modules in three stages. The first stage would be the pre-production of 80 TOB modules as described in the previous section. This would be followed by a ramp-up to peak production spanning 6 months and comprising 600 modules. In this period we would refine all high rate production and quality assurance procedures. This would be followed by a two-year full production period in which the remaining 6000 modules would be produced. The main module production steps are as follows:

- Probing of Sensors (a few % of all)
- Module Assembly
- Optical Inspection (~10% of all modules)
- Wirebonding (2 wires per channel: either 1024 or 1536 wires per single-sided module)
- Repair
- Testing (Hybrids and completed modules)
- Sandwiching single-sided modules to make double-sided modules.
- Installation of modules in support rods
- Burn-in of modules on rods
- Independent quality assurance testing
- Receiving of components and shipping of completed rods
- Documentation and inventory control

The USA consortium plans to base TOB module production at the FNAL Silicon Detector Center (SiDet). As discussed later in greater detail, there is a good chance that this project will overlap the Run 2b Silicon upgrades for the CDF and DØ experiments. To avoid capacity constraints brought on by an overlap of peak demand or the need to increase production beyond the anticipated steady rate for whatever reason, we are prepared to shift a portion of our production to a second assembly center. This could be achieved by transferring one of the gantries and one of the test stands to the new location. The setup of a second facility would require the purchase a high-speed wirebonder for that location. This additional cost is therefore included in the contingency for the project (see below). However, SiDet capacity is large enough that it is very unlikely that we would need to stop all CMS production there.

Table 5 lists the clean room and working space areas at SiDet. Currently Sidet has an installed machine base of 16 Coordinate Measuring machines (CMMs), 5 automated wirebonders, 2 automated optical inspection systems and a variety of probe stations, DAQ systems, microscopes, and other useful equipment. The work force at SiDet includes roughly 20 trained CMM operators and 7 wirebonder operators as well as a complement of roughly 20 other technicians engaged in light assembly, and facility maintenance.

CLEAN ROOM		SEMI-CLEAN & GENERAL WORK	
Lab D	218 m^2	Lab D Test Area	138 m^2
Lab D extension	74 m^2	Crossover (Autumn 1998)	114 m^2
Lab C	293 m^2	Lab B	500 m^2
Lab A	272 m^2		
Total	*857 m^2*	*Total*	*752 m^2*

Table 5. SiDet clean room and work space.

All setup of procedures and all production and testing of modules at SiDet will be managed and overseen by experienced physicists in the group. During production, physicists from all collaborating institutions will work at FNAL in shifts. The overall distribution of responsibilities is represented in Table 6. As can be seen from the table, we plan to have most production work occur at FNAL. Initial sensor probing will be done at Kansas State U. (KSU), and U. of Illinois at Chicago (UIC). U. of Kansas (KU) will provide support in setting up the DAQ test stand and also all hybrid testing. U. of Rochester together with FNAL will take responsibility for the design of the cooling setup and its associated interlocks for the burn-in system as well as the design and fabrication of the transportation boxes. Module assembly, wirebonding, and assembly into rods will be the responsibility of FNAL. Testing and burn-in will be the shared responsibility of FNAL and KU. Module repairs will be performed by Purdue and FNAL.

In the following sections of this note, we detail the production plan of the USA Consortium including our estimates of cost and schedule. We also discuss the possible overlap of this project with other FNAL programs, and our contingency plans.

Task	Location	Responsible Party
Sensor probing	Universities	UIC, KSU, Northwestern
Hybrid testing	FNAL	KU
Module assembly	FNAL	FNAL
Bonding	FNAL	FNAL
Testing	FNAL,KU	FNAL,KU
Rod assembly	FNAL	FNAL
Cooling setup	FNAL	Rochester,FNAL
Interlocks	FNAL	Rochester,FNAL
Quality control	UIC	UIC, Northwestern
Burn in testing	FNAL	FNAL,KU
Repair	FNAL,Purdue	FNAL,Purdue
Transportation Boxes		Rochester

Table 6. Distribution of responsibilities.

3. Cost and Schedule

The cost and schedule for the production of the TOB modules by US CMS is discussed in this section. For the estimation of most of the module production tasks we have drawn on the experience of the CDF ISL project. The CDF ISL half-ladders are similar to, but somewhat more complicated than, the TOB modules. Similarities include front-end electronics hybrids mounted off of the silicon and simple Carbon fiber frame supports for Silicon and hybrids. The differences include the fact that the ISL half-ladders are made manually with special fixtures, contain 3 double-sided sensors rather than 2 single-sided ones, and have double-sided hybrids. The manual assembly time for an ISL half-ladder is approximately 1.5 h. Wirebonding of ISL half ladders involves 1024 channels with 3 wires per channel. Pitch adaptor bonds are also made but these are done on the hybrids prior to assembly. The total number of wirebond wires per ISL half-ladder is thus 3072, which is 2 to 3 times more than the number in a TOB module. Repairs are required for essentially all ISL half-ladders but usually only involve disconnection of bad channels and take less than one hour per module. The ISL production has gone very well, with a predictable, steady pace as seen in Figure 7. Furthermore, the quality of the half-ladders produced is extremely high. For example, the alignment of sensors in the plane is typically good to within ±2 μm in both x and y and the modules are typically flat to within ±23 μm. The creation of bad strips during production averaged only 0.4%.

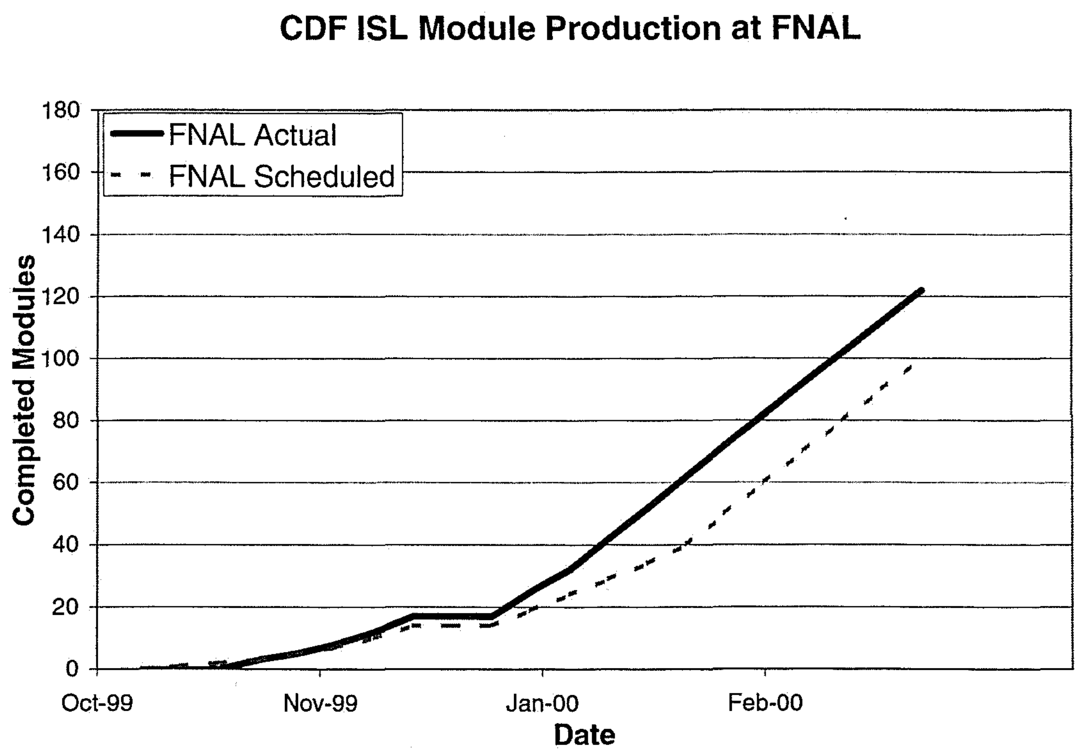

Figure 7. CDF ISL module production experience.

The use of single-sided silicon and hybrids in CMS represents a significant simplification relative to the already rather simple design of the CDF ISL half-ladders. In particular, single-sided Silicon is now a real industrial product for which there exists large commercial capacity. Hamamatsu Photonics Corporation and SGS Thompson each have the capability of processing tens of thousands of wafers per month. In addition, the quality and performance of the sensors is excellent. As an example, the CDF Layer 00 project placed an order for single-sided 25 μm pitch detectors in 1999. The final specifications were agreed upon in August and the detectors were delivered in November. Of the 200 detectors delivered, 170 had no bad strips while the remainder had only one bad strip (0.05 – 0.10 % bad strips on average). The detectors all held bias voltages of the order of 700 V. Single-sided CMS TOB prototype sensors were produced by Hamamatsu with similar characteristics. We expect that the higher quality of the sensors, together with the fact that the strip sides are never touched during assembly, (as in the case of double-sided sensors), will result in significantly lower repair requirements.

The project will be made up of three distinct periods, as mentioned earlier. The pre-production period will last 5-6 months and result in 80 modules. The majority of effort in this period will be toward establishing the equipment and procedures for module assembly. This period will be followed by a 6 month ramp-up in which 600 modules are produced at a pace varying from ~2 per day at the start to ~10 per day at the end. In this period we will concentrate on the establishment of high rate production procedures that maintain quality and safety. The final major production period will then last two years and result in 6000 modules being produced at a pace of ~ 12 per day. A model was used to estimate the labor requirements and cost for these three periods based upon the production steps outlined earlier and our experience with CDF ISL module production. The contingency for the labor estimate was determined by first adjusting the basic estimates to account for continuity of the work force, taking into account the actual Full Time Equivalents (FTE) required to maintain the effort indicated by the model. This results in about a 10-20% increase. Next, we assumed that the production could be delayed or otherwise hampered and that in order to meet the schedule, production would have to be doubled for a period of 6 months. This is a somewhat ad hoc contingency plan, but one that we believe is reasonable based upon our experience and a current analysis of the tracker project. Our resulting labor cost estimates are contained in the project file appended to this note. The total technician labor cost is 1,063k$. With standard US CMS methodology we find an estimated contingency of 457k$. Beyond module production, there are labor costs anticipated for the assembly of TIB shells. We estimate this cost to be 126k$ with a contingency of 71k$. The fixtures required for shell assembly will be provided by INFN-Pisa.

Production Phase	**Duration**	**Modules**	**Technical Labor Cost**
Pre-production	5-6 months	80	31k$
Ramp-up	6 months	600	119k$
Production	2 years	6,000	913k$

Table 7. Technical labor costs for various phases of module production.

Item	**Base**	**Contingency**	**%**
Probe Station	50k$	22k$	44
Assembly Equipment	211k$	68k$	32
Wirebonder Equipment	66k$	264k$	400
Test Stands	225k$	126k$	56
Burn-in cooling stand & interlocks	100k$	56k$	56
Clean Room Supplies	60k$	13k$	21
Miscellaneous Instrumentation	50k$	63k$	125
EDIA	378k$	166k$	44
Equipment Setup & Maintenance	110k$	93k$	85
Storage, test & shipping boxes	115k$	76k$	66
Transportation	102k$	204k$	200
Totals	**1,467k$**	**1,151k$**	**87%**

Table 8. M&S and EDIA costs, contingency and percent contingency.

In addition to the cost of labor, there are engineering, machining, equipment, operating, and transportation costs. These are summarized in Table 8. The base equipment cost includes 211k$ for two gantry assembly setups whose price is relatively well known as a result of the purchase of such a system by CERN. The cost of setting up and maintaining the gantry and test stands is non-negligible. Some involvement of engineers and higher level technicians will be required. We have included a cost of 110k$ to cover this for the duration of the project. The test stand cost is not completely understood at this time. Based upon information we have received, we estimate the cost of a single APV test stand at 40-50k$ and expect we will need at least 4 stands. In order to catch possible bonder-induced damage, there will be one test stand in the wirebond area. Another stand will be dedicated to full tests of modules and hybrids, and a third will be needed to operate the burn-in system. Another one or two stands are likely to be needed at Universities where additional quality assurance and repair will be done. It is conceivable that a low-cost pc-based basic test stand will be developed which could be used for most purposes at lower cost. Currently, we are forced to assume that all test stands will be full DAQ stands. The cost of a single burn-in cooling stand has been estimated at 50k$. It will be necessary to have a second burn-in stand, which will be particularly useful if a second production site is required. For probing of sensors, KSU has most of the equipment required but has estimated 50k$ in additional costs to make their systems conform to the tests planned by CMS.

Storage, testing, and shipping boxes will play a significant role in assuring the protection of modules and completed rod sub-assemblies during production, testing, and transportation to CERN. Typically test boxes cost $300 each and we expect that we will need several hundred of them. Transportation boxes for hand-carrying 50-100 modules in rods to CERN will need to be air tight, dry, protect modules from vibration or shock, and have some active or inactive monitoring devices. We have estimated a cost of 5k$ per box and a need for 6 boxes. Finally, during production, silicon and completed modules in various stages of assembly and testing will require dry storage containers. These cost roughly 1k$ each and we estimate that we will need of order 35 such containers to handle the large quantities of components involved in this project.

For transportation we are assuming that we can design a transportation box that can occupy a standard economy seat and transport up to 100 modules. Our plan would be to ask those US CMS members traveling to CERN to carry completed modules (after some training). This would allow us to keep the cost to 102k$ or so for the cost of the additional fares (of order 70 round trips). If however the transportation requires dedicated trips, then the cost could rise substantially, explaining the large contingency associated with this task.

Another item with large contingency is wirebonder equipment. The base cost of 66k$ includes the price of fixtures for module support during bonding and 50k$ for a material handling system designed specifically for the K&S 8090 bonder. The latter would enable a more automated approach to the loading and bonding of modules, thus limiting manpower costs. If it turns out that SiDet does not have enough wirebond capacity, then it could be necessary to purchase an additional K&S 8090 and associated material handling system at a cost of roughly 264k$. Note that we estimate the capacity of SiDet for wirebonding CMS TOB modules at roughly 32 per 8 hour shift. Thus, if we need to maintain an accelerated production rate of 24 per day toward the end of the project, as discussed earlier, we would use most of the SiDet wirebonding capacity. This would produce conflicts with other FNAL projects. For clean room usage we estimate disposable gowns, booties and other typical production materials like epoxies, wipes, etc. will cost roughly 2k$/month. For the duration of the project, this results in a cost of 60k$. For miscellaneous instrumentation equipment, such as special inspection microscopes and measuring devices, we have included a cost of 50k$. Finally, for basic support of the project, and based on past experience on Tevatron projects, we have included the cost of 0.5 FTE engineer, 0.5 FTE designer, and 0.5 FTE machinist support for the duration of the project at a total base cost of 378k$.

Item	**Cost**	**Contingency**	**%**
Module Production Labor	1,063 k$	457 k$	43%
Shell production & Rod assembly	126 k$	71 k$	56%
Equipment	1467 k$	1,151 k$	87%
Totals	**2,656** k$	**1,679** k$	**78%**

Table 9. Summary of total costs, contingency, and percent contingency.

4. Funding.

The total cost of this project is seen to be 4,335k$ of which 1,679k$ is contingency. The project described in this note, if approved, would supersede the previously approved project to build the inner two layers of the TIB. For that project, the total cost of 518k$ was to be obtained from the FNAL base program in repayment of in-kind contributions from International CMS to laboratory programs. This money would be applied to the TOB project leaving a total cost of 3,817k$ of which 2,339k$ is base, and the remainder is contingency. The additional base cost of 2,339k$ would be provided by US CMS in FY01, as part of a release of approximately 5.9M$ of contingency based upon cost performance of the project up to that time.

5. SiDet Requirements

As mentioned earlier, the schedule for the production of CMS modules extends to roughly the end of calendar year 2003 which is likely to mean some overlap will occur with the Run 2b CDF and DØ Silicon replacement projects. The latter are still in the early planning stages but both experiments currently project a likely need to replace at least portions of the Run 2a Silicon systems in 2004. In addition to these projects, there is the possibility that SiDet will be engaged in the production of the BTeV and CMS pixel detectors. In this section we will discuss the capacity usage of all of these projects and discuss the likelihood that they can co-exist in SiDet.

Despite the large number of modules involved, the CMS TOB project requires relatively modest space. The module assembly is automated by means of a gantry system, which takes up relatively small space as compared to the CMMs used in module assembly for Run 2a detectors at SiDet. Also, because the volume of production of the gantry system is large, we expect that two such systems will be more than adequate for the project. The two gantries would take up only of order 15% of the Lab D module assembly area. Module wirebonding would be relatively straightforward and in steady state production will require about two-thirds of the capacity of one of the two K&S 8090 high-speed machines. If we experience delays and need to double our production rate, this would double. At that point we would be using the majority of the K&S 8090 wirebonding capacity at SiDet. If this occurs when other projects are also at peak, we believe it will be a problem. To remedy this, we have included the cost of a new K&S 8090 in our contingency estimate. The plan would then be to buy a machine that would be dedicated to CMS mircrostrips. Of the remaining two K&S 8090s, the CMS microstrips would need roughly one-third of one machine in the worst case. Beyond assembly and wirebonding the project will also need space for testing, burn-in and storage of module components and completed modules. The storage space requirements will be minimized by maintaining inventory for several months worth of module production only, and we plan to ship completed modules on rods to CERN as quickly as possible. The amount of space required for testing, burn-in, and storage is therefore 55 m^2, which is equivalent to roughly half of the existing burn-in area in the SiDet cross-connect building. CDF and DØ currently share this 114 m^2 area for Run 2a production testing and burn-in. Finally, the CMS Silicon project will also need the 3m B&S CMM for the construction of the inner barrel shell supports. This work will likely occur in 2001-2002, starting after the Run 2a FNAL projects are complete and finishing before the Run 2b replacement effort gets underway.

In summary, the CMS microstrips production effort will require ~15% of Lab D module assembly area and an area of 55 m^2 or so for testing and burn-in. It will also require a sizable portion of the wirebonding capacity, particularly if production needs to be bumped up for whatever reason. In response to the wirebonding issue, we have included enough contingency to alleviate the problem. The total impact on SiDet capacity is therefore small. However, the scale of the Run 2b Silicon replacements is not yet known and the addition of BTeV and CMS pixels in this period will mean that SiDet capacity could be stretched.

To understand the needs of the Run 2b Silicon replacements is difficult at this time. However, it is relatively clear from the initial studies and leanings of the Silicon groups for both CDF and DØ that the replacements will be either of smaller scale or of simpler design than the original Run 2a systems. For example, one possibility would be to replace only those layers of Silicon, which are radiation damaged. This would mean projects that are one-third the scale of the original ones. Alternatively, both groups are considering replacing large portions of the Run 2a Silicon with simple modules and mechanics similar to the CMS tracker design. These would use single-sided Silicon and mount electronics off of the Silicon. As a result, module production would be very much simpler and more reliable. In fact, as mentioned below, the CMS automated assembly methods could well be translated to such modules. This would greatly reduce the space and labor needs of these projects. In either case, it is already known that the CDF ISL detector will not need to be replaced. Similarly, DØ is not planning to replace the Run 2a disks. Assuming conservatively that CDF and DØ replace all other Run 2a silicon systems, and do so in the same space and labor-intensive manner as for Run 2a, then these replacement projects would need roughly 60% of all SiDet capacity. In discussions with BTeV and CMS pixel groups[5], we estimate that these projects will require roughly 25% of SiDet space and wirebonding capacity. Therefore, in the worst case, SiDet will have 15% free capacity for CMS Silicon microstrips. For tasks other than wirebonding, this is comparable to what is required for this project. Furthermore, these projects will likely be in conflict only during the latter part of the CMS microstrip effort.

We conclude that SiDet will very likely have enough capacity to accommodate the CMS Silicon microstrips project without negatively impacting other SiDet users. Furthermore, the technology imported for this project will probably have a positive impact on the Run 2b Silicon replacement projects as discussed in the next section. Nevertheless, in case there does happen to be a serious conflict for SiDet resources, we plan to prepare a second module assembly site at one of the participating Universities of our group where there already exists some infrastructure and module assembly experience. To achieve this, we would transfer one of the two gantry systems to the remote site, as well as a test stand and burn-in station for module testing and burn-in. The only possible additional expense would be the need to purchase a high-speed wirebonder for the second site. In this way, we believe we are prepared to maintain our production goals regardless of the evolution of the many projects to be carried out at SiDet.

6. Interactions with FNAL projects

As mentioned above, the CMS Tracker Outer Barrel module construction will be based at Fermilab during the period of January 2001 – December 2003. At this time CDF and DØ will be taking data in Run 2a. The Silicon detectors of both experiments were designed for $2 fb^{-1}$ of integrated luminosity. With the exception of CDF's L00, all of the silicon sensors used in these experiments are only radiation hard to ~2 Mrad and the inner layers of these detectors will survive to accumulate ~5 fb^{-1} of data. On the other hand, there is now clear physics motivation for the Tevatron to accumulate considerably more data. At 30 fb^{-1} of integrated luminosity, a so-called Run 2b, could enable the Higgs discovery to occur at the Tevatron. This means that the

Silicon detectors have to be at least partially replaced with more radiation hard detectors. It is anticipated that the replacement will take place during a shutdown in late 2003 – early 2004. Low resistivity microstrips seem to be the only radiation hard technology that would satisfy this very tight time scale. But this means that two more silicon detectors have to be built at SiDet on the same time scale as CMS. Moreover many of the physicists involved in CMS are also involved in Run 2b. This certainly creates some interference. While the negative components of this interference, like sharing SiDet facilities, engineers, and technicians, are obvious, there are positive effects as well. For most of our group, it is our ***physics interests,*** which motivate our involvement in CMS. The LHC program is a logical continuation of the Tevatron program and the only opportunity to continue working with real data at the energy frontier in the period starting 5-7 years from now. There is a substantial interest to organize algorithm development (e.g. heavy flavor tagging) and physics studies (e.g. new physics in the ttbar system) in our group. In this way the Tevatron experience will be naturally used to great advantage in the CMS physics program.

One of the worries of small university groups is that they will be lost inside the multinational CMS collaboration. Fermilab, as an umbrella organization, strengthens each individual contribution. On the other hand, having the CMS construction project clustered around Fermilab is a wise way for Fermilab to remain a major center of physics. It is also the best way to ensure that CMS construction and Run 2b projects are made as collinear as possible in order to minimize any negative interference. We are trying to organize this project in a manner that takes into account Run 2b commitments and interests. For example, the University of Kansas took responsibility for hybrid testing for CMS as well as for DØ in Run 2b. Similarly Kansas State University signed up for sensor probing for both projects, and University of Illinois at Chicago – for quality control. This way, though the workload is increased it is not doubled, and experience can be integrated and shared across several projects.

CERN has had an extensive, long-term, R&D program to develop radiation hard components for silicon detectors. Significant progress has been achieved and Run 2b projects plan to benefit from these studies. Working on the CMS microstrip silicon tracker is the best way to import the radiation hard silicon technology to the US. Moreover, since CMS is closer to the production stage, many procedures are well specified and documented, which makes them easier to set up and helps limit their impact on Run 2b projects. CMS ideas for mechanical support systems for Silicon detectors are also extremely attractive in their simplicity. Development work on these systems at CERN and elsewhere in Europe can be used to the benefit of Run 2b projects by presenting simpler, more affordable ways to assemble large-scale Silicon detectors. Last, but not least, CMS has invested a significant amount of time and money in the successful development of module assembly automation. Run 2b projects will likely benefit from this as a result of our direct use of such systems for CMS microstrips. For example, the CMS automated module assembly gantry is flexible enough to incorporate different module structures allowing it to be easily altered for use in CDF and DØ Run 2b projects.

Overall, we firmly believe that our involvement in the CMS Silicon microstrips project will have extensive benefits for Fermilab and US physics.

7. Conclusions and Summary.

In summary, we are proposing to build ~6600 single-sided-equivalent modules comprising the CMS tracker outer barrel. We would also test, burn-in, and assemble these modules into rods, which would be transported to CERN for final installation. Our group has significant experience from FNAL Tevatron Silicon projects and hadron collider physics that will benefit CMS overall. Similarly, FNAL facilities at SiDet are optimal for this effort and this project would provide important continuity for the SiDet work force. The total cost of the project is estimated at 2.6M$ with a contingency of 1.7M$. The effort would span the period from January 2001 to November or December of 2003. Relatively modest manpower, space and equipment at SiDet are required for this effort. The project is expected to overlap other important FNAL efforts at SiDet but our analyses indicate that SiDet capacity is adequate to accommodate all of the users foreseen. Nevertheless we are prepared to shift a substantial fraction of our production to a collaborating institute in order to avoid conflicts which may arise. We believe this project will be beneficial to FNAL, US CMS, and also the CDF and DØ Run 2b Silicon replacement efforts.

Attachments:

Appendix 1: Work Breakdown Structure and Schedule

Appendix 2: Contingency Spreadsheet

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[1] CMS Collab. *Addendum to the Tracker TDR*, CERN/LHCC 2000-016, February 21, 2000

[2] CMS Collab. *The Tracker Project Technical Design Report*, CERN/LHCC 98-6, April 15, 1998

[3] D. Stuart, *Effects of Material in the CDF-II Silicon Detectors*, CDF Note 5268, March 29, 2000

[4] CDF Collab., *Proposal for the Enhancement of the CDF II Detector: An Inner Silicon Layer and A Time of Flight Detector*, Fermilab-Proposal-909, October 28,1998

[5] For BTeV we have discussed SiDet needs over time with Simon Kwan. For CMS pixels we have discussed capacity requirements with Bruno Gobbi.

US CMS Si Tracker P[illegible]

J. Incandela

PAC Meeting

Aspen

June 18, 2000

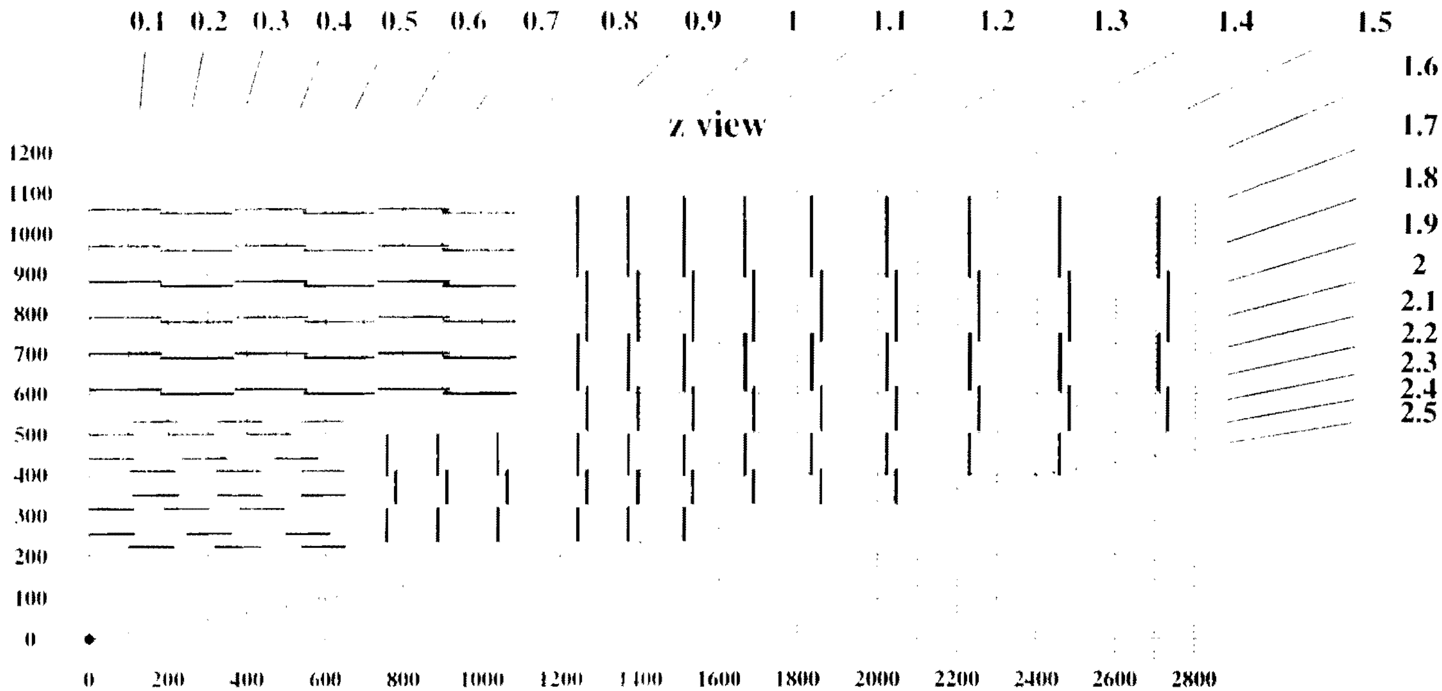
Silicon Tracker G[redacted]

- Fermilab
  - B. Flaugher, J.Goldstein, J.Incandela, R.Lipton, P.Lukens, S.Mishra, T.Nelson, P.Rapidis, L. Spiegel, D. Stuart, S.Tkaczyk
- Kansas State University
  - T.Bolton, R.Demina, M.Kubantsev , W.Reay, R.Sidwell, N.Stanton
- Northwestern University
  - D. Buchholz
- Purdue University
  - I.Shipsey, D.Miller
- University of Illinois, Chicago
  - C.Gerber
- University of Kansas
  - A.Bean, P.Baringer
- University of Rochester
  - S.Blusk, M.Kruse, P.Tipton

Out

- Recent Developments
  - All Silicon Tracker Decision and Current Layout
- Organization of CMS tracker group into consortia
  - Role of proposed US Consortium
- Cost and Schedule

Tracker Layout



- December 1999 - Decision to use silicon in the outer tracker.
- April 2000 - New Layout approved
  - 10 barrel layers, 3 small disks and 9 forward disks.
    - 5 barrel layers and 3 disk rings rings have 100 mrad stereo (blue)
    - Increase surface area from < 100 m² to ~240 m²

Desc

- Tracker Inner Barrel (TIB)
  - 4 layers with 300 μm thick sensors.
    - Modules tilted 9° in "shell" support mechanics
    - 2 innermost layers DS
- Tracker Outer Barrel (TOB)
    - 6 layers with 500 μm thick sensors
    - Layers 1,2 and 4 DS
  - Modules contained in "rod" support mechanics
- Tracker Small Disks (TSD)
  - 3 small end-cap disks/end
    - Each has 3 rings
    - Rings 1 and 2 are DS
    - 300 μm thick sensors
  - "petal" support mechanics
- Tracker End Cap (TEC)
  - 9 large end-cap disks/end
    - each has 7 rings
    - 3 inner rings same as TSD
    - Ring 4 has 300 μm thick sensors
    - Outer 3 rings have 400 to 500 μm thick sensors
    - Rings 1,2 and 5 are DS
  - "petal" support mechanics

Barrel Si

TIB

Layer	Radius [mm]	Modules In ϕ	Total Modules	APV Chips	ϕ pitch [μm]	Stereo [μm]	Total APV's
1	239	28	336	6+6	80	80	4032
2	331	38	456	6+6	80	80	5472
3	423	46	552	4	120	-	2208
4	515	56	672	4	120	-	2688

TOB

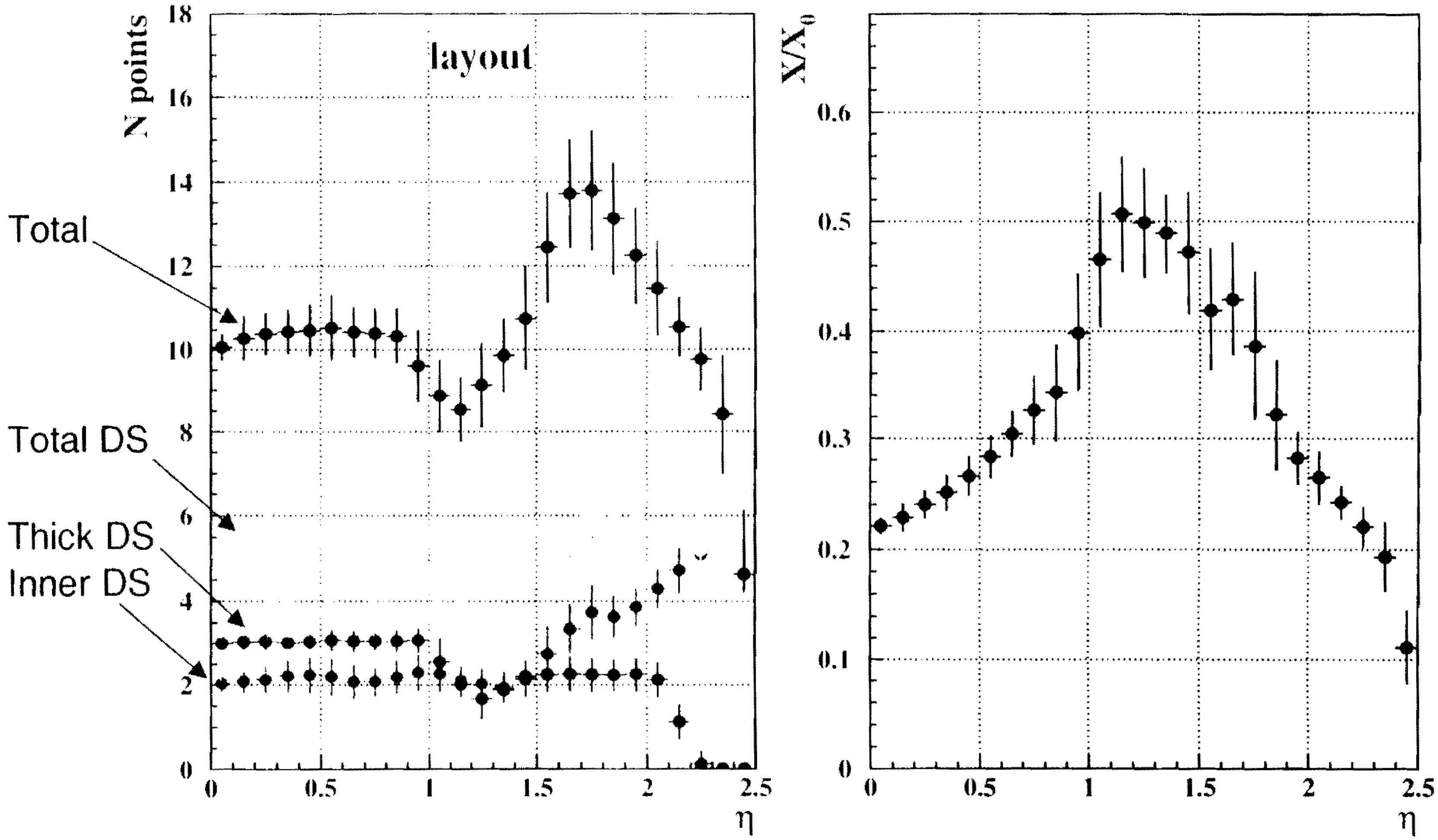
Layer	Radius [mm]	Modules In ϕ	Total Modules	APV Chips	ϕ pitch [μm]	Stereo [μm]	Total APV's
5	605	42	504	6+4	122	183	5040
6	695	48	576	6+4	122	183	5760
7	785	54	648	4	183	-	2592
8	875	60	720	4+4	183	183	5760
9	965	66	792	6	122	-	4752
10	1055	74	888	6	122	-	5328

Forward

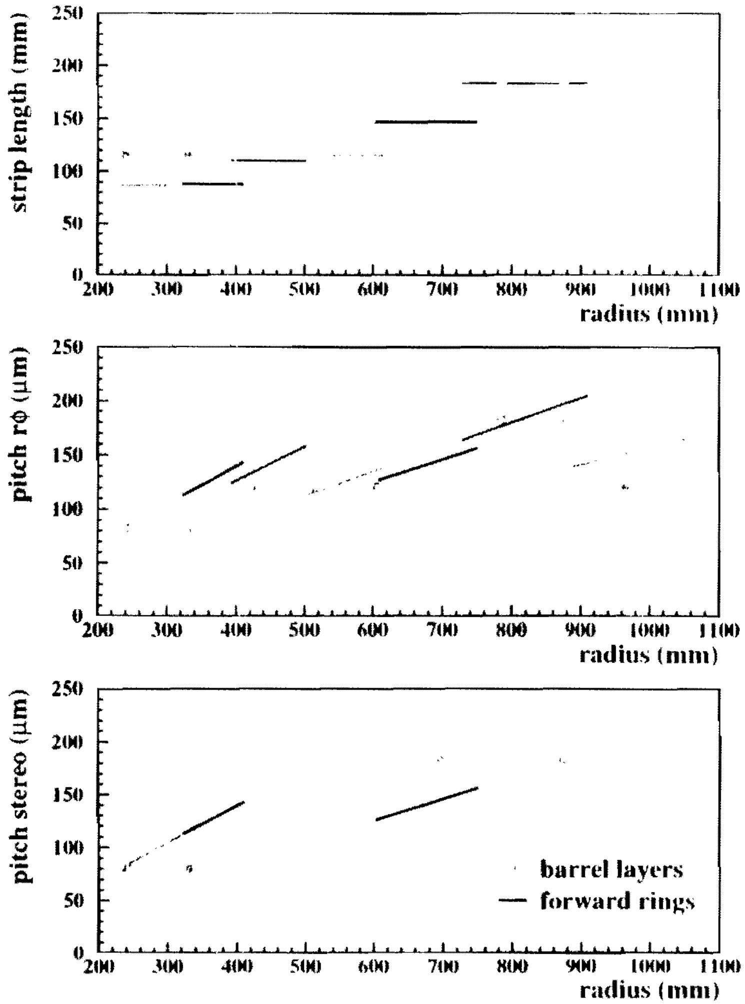
TSD +
TEC

Ring	Modules In ϕ	No. of Rings in z	Total Modules	APV Chips	Pitches ϕ [μm]	Stereo [μm]	Total APV's
1	24	12	288	6+6	81/112	81/112	3456
2	24	18	432	6+6	113/143	113/143	5184
3	40	22	880	4	123/158	-	3520
4	56	18	1008	4	113/139	-	4032
5	40	18	720	6+6	126/156	126/156	8640
6	56	18	1008	4	163/205	-	4032
67	80	18	1440	4	140/172	-	5760

Layers,Material traverse



Pitch vs Radius



- TIB
  - 1224+ 792 SS+DS modules
  - 2808 6” wafers
  - 14400 APV chips
  - 5.5 M wirebond wires
- TOB
  - 2328+1800 SS+DS modules
  - 11856 6” wafers
  - 29232 APV chips
  - 11.2M wirebond wires
- TSD+TEC
  - 1888+720 thin SS+DS modules
  - 3328+2448 thick SS+DS
  - 3328+7776 thin+thick 6” wafers
  - 34624 APVs
  - 13.3 M wirebond wires

Tracker Group Orga

- 4 Consortia with proposed roles as follows:
  - Central Europe (CE): (previously MSGC groups)
    - All Forward Modules (TSD + TEC) and installation in pedals.
    - Assembly of TSD+TEC
  - CERN
    - Overall integration, general support structures, cooling and inert gas flow. Position monitoring and alignment. Mechanics, cooling and final assembly of the outer barrel....
  - INFN
    - Responsible for Inner barrel modules (TIB)
    - TIB Mechanics and assembly of the inner barrel.
  - USA
    - All Outer barrel modules (TOB) and installation on rods
    - assemble some support structures for inner barrel

LHCC

The LHCC has approved the Tracker TDR Addendum during its last session 17-18 May. The LHCC believes that the full silicon tracker as proposed by CMS is very elegant. The simplified layout has many virtues. I append an extract from a message sent by Giorgio Goggi to the EP Division:

'Addendum to the Tracker TDR: streamlined concept and enhanced performance.Very good progress on layout, logistics, maintenance, installation, detector and system design'

Congratulations to the Tracker community for this beautiful achievement.

- Michel

Tracker Outer Barre

l=91.514 w=93.696 dl=1.5 dw=1.35 gap=0.1 2*l+2*dl+gap=186.128 Ltot=189.128 Wtot=96.396	P1=122 P2=183	

- ϕ(stereo) pitch = 122 (183) μm
- Sensors sensitive areas 91.514 x 93.696 mm^2
- Assumed non-sensitive regions 1.5 (1.35) in length (width)
- Gap between two sensors 100 μm
- Length (width) of silicon in module = 189.128 (96.396) mm

Tracker S

- Preproduction (200 modules) Nov.2000 - Aug.2001
  - TOB (US CMS) will build roughly 80 modules
  - The exercise calls for use of final production methods
    - We need to set up a gantry system (purchase in early FY01).
    - We need to setup a test stand and some preliminary version of a burn-in system with interlocks this Autumn/Winter.
    - Right now many parts are being purchased/prepared for us in Europe. We will need to pay for them in FY 01.
- Module Production Aug. 2001 - Jan. 2004
  - TOB however needs to be completed earlier
    - Installation of rods into the outer wheels Jun.2003 - Dec.2003
    - We would aim to complete module production by Autumn 2003

  ⇒Overlap with FNAL Collider Run 2b silicon upgrades

Production Tas[redacted]

- Technician tasks included in cost estimation:
  - Probing of sensors (few % of total)
  - Module assembly and Module inspection (~10 % of total)
  - Wirebonding (average of ~5 APV/module x128 channel/APV x 2 wires/channel = 1280 wires/module)
  - Repairs (Minor repairs at 50% level ? Significant repairs 5% level ?)
  - Testing (hybrids and completed modules)
  - Sandwiches of 2 Single Sided modules for Double Sided layers
  - Installation on Rods (6 modules per)
  - Burn-in on rods
  - Quality assurance testing (0.2% to 10%)
  - Receiving and shipping of components and completed rods
  - Documentation and inventory control
- All setup of procedures and all production and testing will be managed and overseen by physicists in the group (in shifts)

Relev[redacted]

- CDF ISL Module Production
  - Simple module design w/Hybrids mounted off silicon
  - Construction is not difficult:
    - Assembly less than 1.5 h.
    - Wirebonding ~ 1 h.
    - Repair ≤ 1 h per module.
- CDF L00 single-sided silicon
  - An industrial product: High quality, rad-hard, Short lead times
    - From final specifications to delivery of all CDF L00 silicon was ~4 months. CMS prototypes similar experience.
  - Commercial capacity:
    - HPK can start 10k wafers/mo.
    - ST-Catania has similar capacity

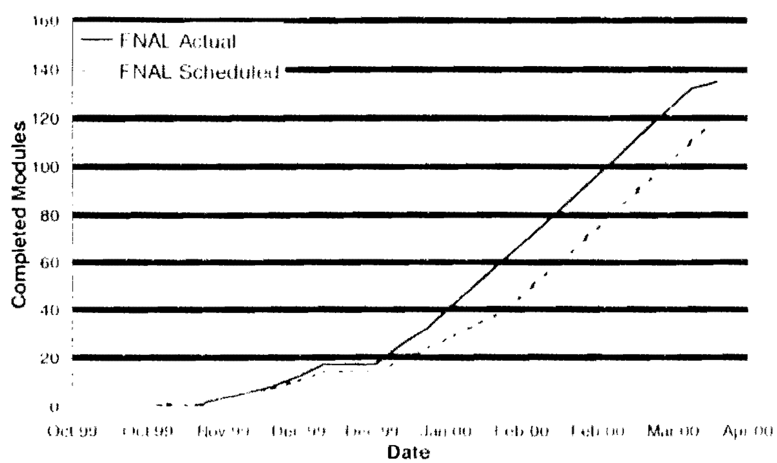
Rad-tolerant Layer 00 Silicon (HPK)

Specications	wide	narrow
# channels	256	128
active area (cm^2)	9.7	4.8
implant pitch	$25\mu m$	
readout pitch	$50\mu m$	
implant width	$8\mu m$	
Test Results		
bad strips (@100 V)	0.10 %	0.047 %
depletion voltage	≈65 V	≈65 V
current @ 500V (nA/strip)	0.5-1.0 typ.	0.5-0.8 typ.

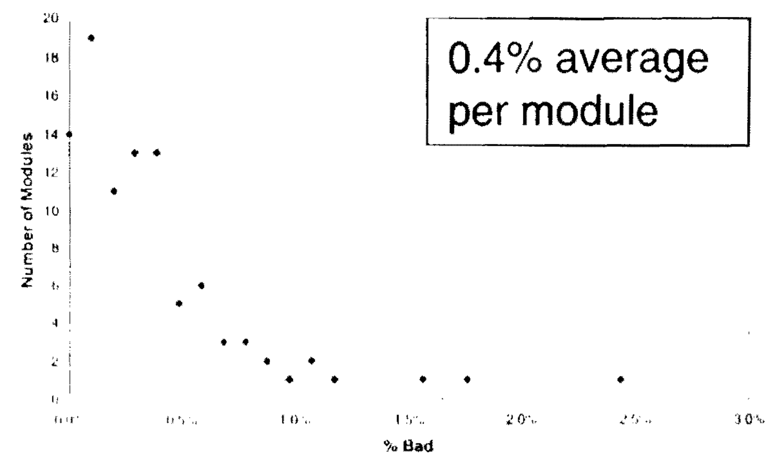
single-sided p-in-n silicon

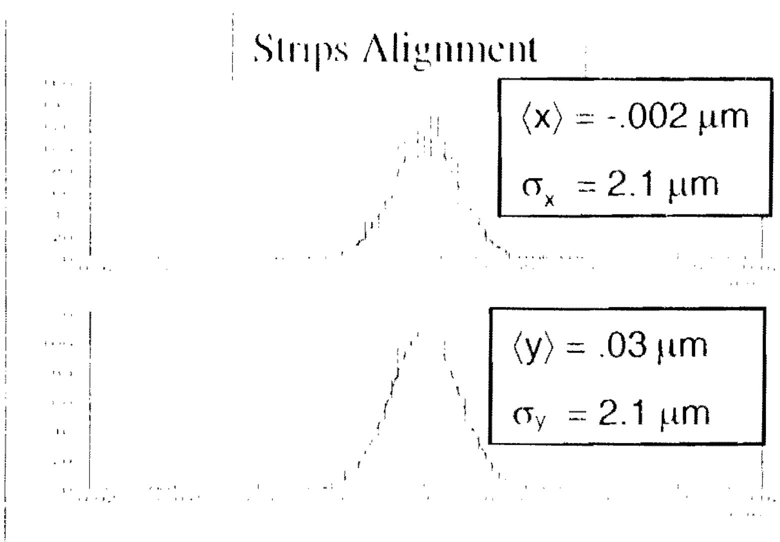
CDF ISL Exper[redacted]

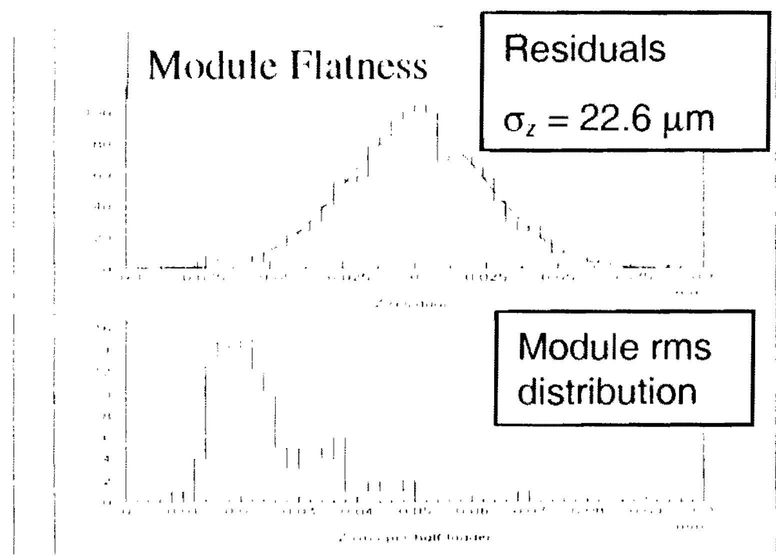
CDF ISL Module Production at FNAL



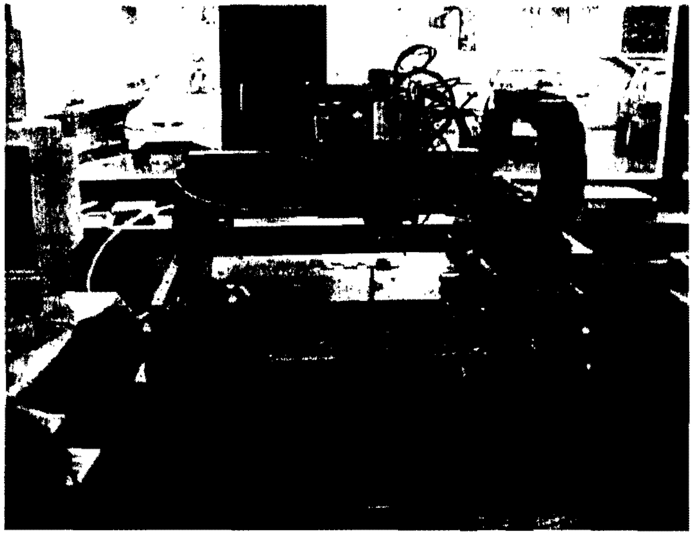
% Bad Strips Formed During Module Production

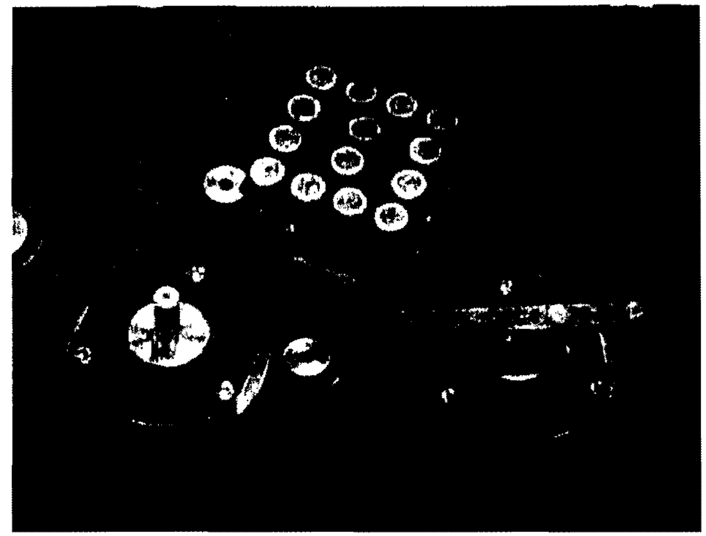




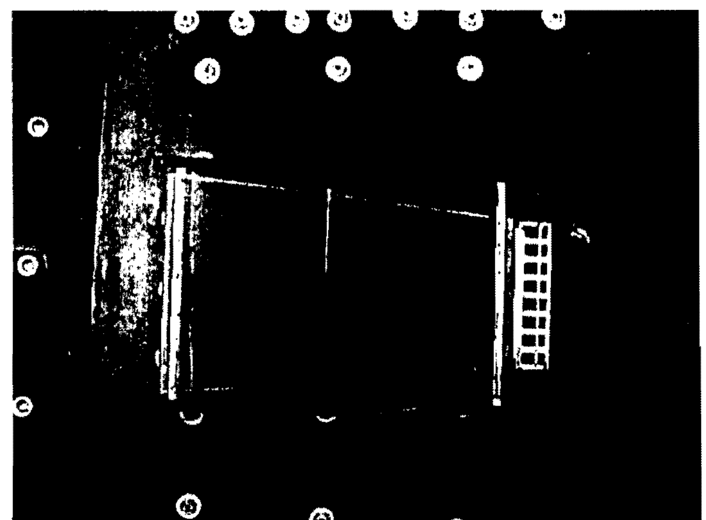


Automated

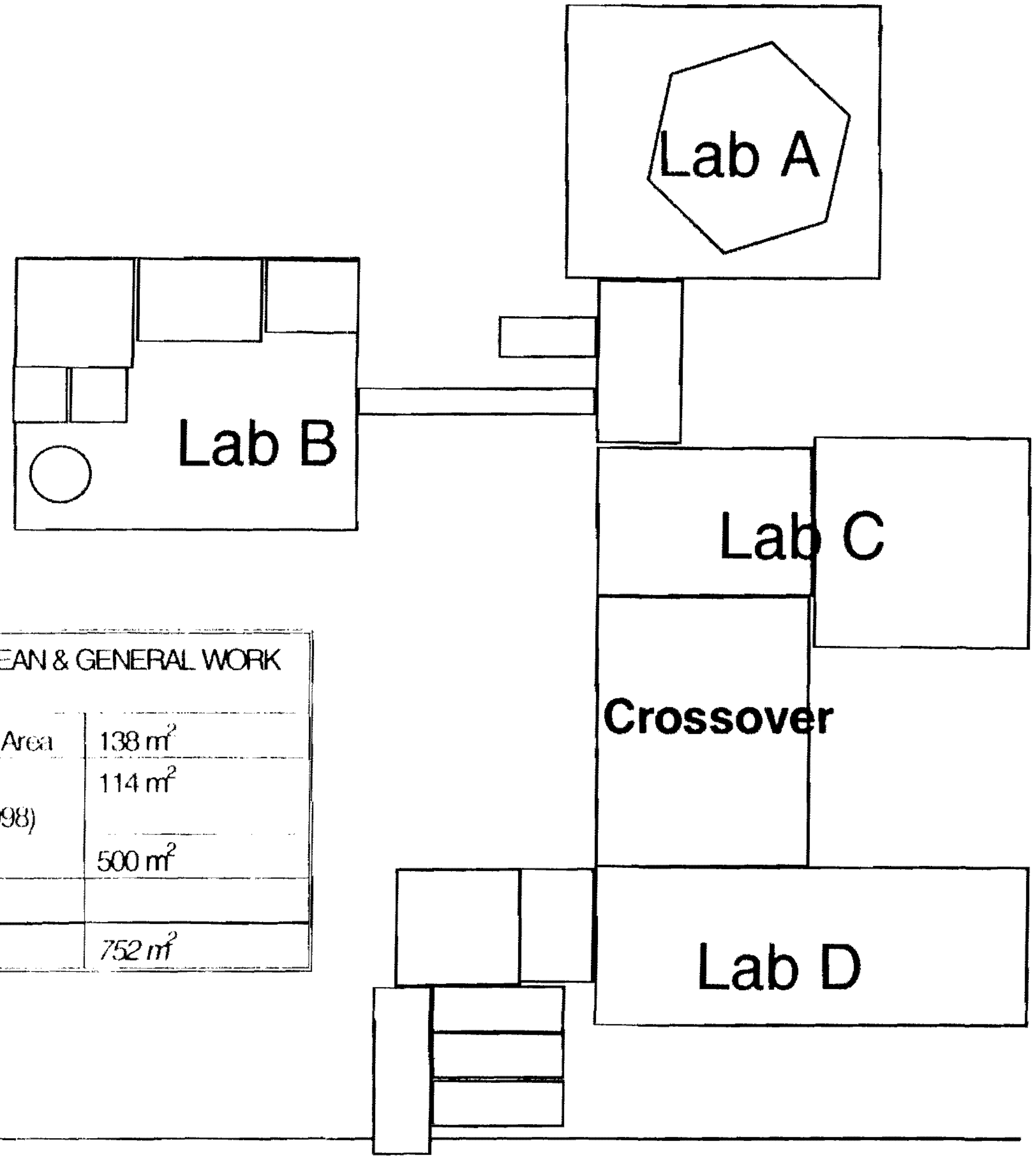




- CERN Automatic pick-and-place
  - Off the shelf hardware
  - Vacuum pieces by CMS
  - 1-2 technicians can assemble 3 TOB modules per hour
  - With 2 K&S 8090 Aluminum wedge wirebonders FNAL can wirebond 4 modules per hour



SiDet Space



CLEAN ROOM		SEMI-CLEAN & GENERAL WORK	
Lab D	218 m^2	Lab D Test Area	138 m^2
Lab D extension	74 m^2	Crossover (Autumn 1998)	114 m^2
Lab C	293 m^2	Lab B	500 m^2
Lab A	272 m^2		
Total	*857 m^2*	*Total*	*752 m^2*

SiDet Equ

- Coordinate Measuring Machines
  - 16 in service, ~20 trained operators
- Wirebonders
  - 5 in service ~9 trained operators

COORDINATE MEASURING MACHINES

MACHINE	CNC/ MANUAL	MEASURING RANGE (X-Y-Z IN METERS)			VOLUMETRIC ACCURACY (MM)
Brown & Sharpe XCEL 123010/5P/UHA	CNC	1.2	3.0	1.0	.012/900
Brown & Sharpe XCEL 091509/5P/UHA	CNC	1.0	0.9	1.5	.012/900
LK G80C	CNC	1.0	2.0	0.8	.013/450
Zeiss UMC850	CNC	0.85	1.2	0.8	.010/400
Zeiss UPMC850	CNC	0.85	0.7	0.6	.008/400
6 Zeiss UMM500	CNC	0.5	0.2	0.3	.005/200
Giddings & Lewis 1808 MZ (2 machines)	CNC	1.0	0.625	0.5	.012/400
Giddings & Lewis 1808 MH	MANUAL	1.5	0.625	0.5	.018/400
Giddings & Lewis 1808 MEA (2 Machines)	MANUAL	0.75	0.625	0.5	.016/400

OPTICAL MEASUREMENT SYSTEMS

MACHINE	MEASURING RANGE (X-Y-Z IN METERS)			PLANAR ACCURACY (MM)
OGP Avant 600	0.45	0.61	0.15	.013/300
Metronics	0.2	0.15	0.15	.013/300

OTHER EQUIPMENT

2 Kulicke & Soffa 8090 Automatic Wirebonders - 5 Hz auto. Bond rate
3 Kulicke & Soffa 1478 Automatic Wirebonder - 1 Hz auto. Bond rate
1 Hughes 2470 V Automatic Deep access wirebonder
1 Kulicke & Soffa Manual (deep access) Wirebonder
4 Probe stations
4 Laser test stands with xy-tables
6 stereo video Microscope with xy-tables for inspection and repairs
2 Omis-II systems

Organization

- Organize main production at FNAL assisted by physicists from all participating institutions
  - Management and QA shifts
  - Transport to CERN
- Outside Institution Roles:
  - Sensor Probing (5-10%)
  - Design/build multi-rod burn-in case(s) w/cooling&interlocks
  - Modules repair
  - Module QA Testing (irradiation/beam-tests/cosmics/lasers)
  - Contingency production
    - To limit conflict with Run 2b, we could set up a second production center outside of FNAL

Division

Task	Location	Responsible Party
Sensor probing	Universities	UIC, KSU, Northwestern
Hybrid testing	FNAL	KU
Module assembly	FNAL	FNAL
Bonding	FNAL	FNAL
Testing	FNAL	FNAL,KU
Rod assembly	FNAL	FNAL
Cooling setup	FNAL	Rochester,FNAL
Interlocks	FNAL	Rochester,FNAL
Quality control	UIC,KU	UIC, Northwestern
Burn in testing	FNAL	FNAL,KU
Repair	FNAL,Purdue	FNAL,Purdue
Transportation Boxes		Rochester

TOB Module Produc

- Preliminary Production model
  - ~ 6000 + 600 + 80 SS equiv. modules + spares
    - Pre-production 80 modules complete by Spring 2001
    - Ramp up with 600 modules Spring 2001 to Oct. 2001
    - Production of 6000 modules Oct. 2001-Oct. 2003
  - Contingency
    - Add 25% labor for continuity
    - Assume that for 6 months we must double our rate
- Production Rates & capacities (At Fermilab)
  - Basic Production Rate = 12 modules/day
    - Pace requires ~70% of a gantry robot, 66% of a K&S 8090 wirebonder, burn-in capacity for 36 modules.
    - Not a lot of space is required.
  - Double rate
    - We need to be prepared to step up to 24 modules/day
    - The only critical issues for SiDet will then be wirebonding capacity and perhaps testing&burn-in space.

TOB Module [redacted]

- Preliminary Production model continued
  - Probing and Repairs (To be done at possibly one or two other collaborating institutes as well as FNAL)
    - Probing (Kansas State University)
      - We can only probe a fraction of all sensors thoroughly. We assume this will be no more than 5-10%. Probing will be done at Universities.
    - Module repairs (FNAL and Purdue)
      - Will likely be at a low level due to the simplicity of the modules and the robustness of the single-sided silicon. We expect two basic classes
      - Simple Repairs (plucking bonds on channels with pinholes) can be done at FNAL
      - Complicated repairs that require more significant debugging may be done outside of FNAL in order to not disrupt production.

TOB Module Produ[redacted]

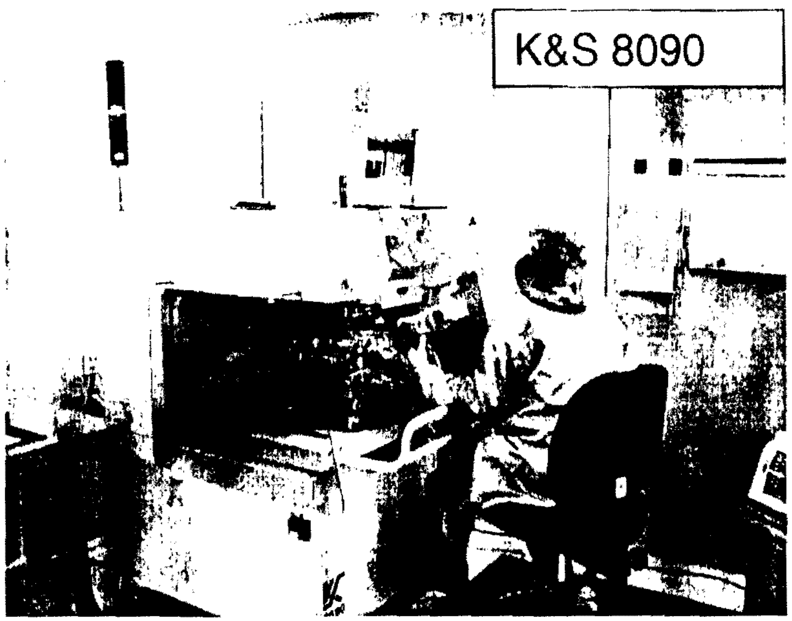
- Preliminary Production model continued
  - Hybrid and module testing & burn-in (FNAL & KU)
    - KU will help to setup test stands at FNAL
  - Extended Quality Assurance Testing (Northwestern & UIC)
    - Sample Testing - to assure quality production of modules at regular intervals in production period
      - Laser Scans (few % level) at FNAL
      - Cosmic Ray tests (Could be done on a stack of loaded rods - maybe even during burn-in at FNAL)
      - Radiation Studies (~0.2% level)

Sidet

- Equipment Requirements
  - Module Assembly: two robots (or 4 CMMs)
  - Cylinder Assembly: 3m B&S CMM
  - Test stands: 4 for module testing, 1-2 for burn-in system
  - Wirebonding: 1-2 K&S 8090 equivalent
- Space
  - Module, Rod, and Cylinder Assembly
    - 100-150 m^2 clean space (~20% of SiDet clean space)
  - Burn-in
    - Roughly half of the Run 2 burn-in space (55 m^2)
  - Storage
    - Plan to receive and ship frequently. Space requirements for storage should therefore be relatively modest.

Space & Equipm

Wirebonding



- SiDet has 5 automatic wirebonders now:
  - 2 K&S 8090
  - 3 K&S 1478
- Run 2 projects peak rate ~3M wires over ~8 months
- TOB: 8M wires in 2.5 years
  - K&S 1478 ⇒
    - 4 modules/shift/machine
  - K&S 8090 ⇒
    - 12/shift
  - Total capacity
    - 36/shift
- Project model ⇒
  - peak at ~67% of capacity.
  - If steady flow then 33% only

Goals

- Schedule
  - We use our experience to plan production in such a way that the probability of on-time completion is extremely high.
- Quality Goals
  - As perhaps the most experienced silicon group in CMS we intend to produce exceptionally high quality modules
    - Minimal losses and maximum quality
      - During pre-production and ramp we will develop iron-clad assembly and wirebonding procedures
        - » With SS sensors, there are ~0.1% inherent bad strips. It may be possible to fabricate with negligible increase in the bad strip count. We want to add no more than ~0.1% additional bad strips. This not only results in better quality, it reduces our work load.
    - Fast feedback to minimize faults
      - We plan to get from module assembly to final electronic test with a minimum of modules in between.

Labor Fo[redacted]

Production Phase	Duration	Modules	Technical Labor Cost
Pre-production	5-6 months	80	31k$
Ramp-up	6 months	600	119k$
Production	2 years	6,000	913k$

Estimates	Modules	Years	Modules/d	Probers	Assembly	Inspect	Bond	Repair	Test	Burn-in	Doc/S&R	Total	Man-years	Cost
Manual	6000	2	12	0.4	4.0	0.4	1.7	0.2	1.5	0.9	1.2	10.3	20.7	$1,127,958
Semi Auto	6000	2	12	0.4	1.5	0.4	1.7	0.2	1.5	0.9	1.2	7.8	15.7	$854,958

- Labor Model
  - Based on CDF ISL
    - Conservative - the base estimate is high by 20-30%
  - Add 2 types of contingency (43% total)
    - Manpower continuity
    - Double peak rate for 6 months
- Module Labor = 1,063 k$ + 457 k$ contingency = 1,520 k$

Equipment, EDIA, Tran[redacted]

- Equipment costs

Item	Base	Contingency	%
Probe Station	50k$	22k$	44
Assembly Equipment	211k$	68k$	32
Wirebonder Equipment	66k$	264k$	400
Test Stands	225k$	126k$	56
Burn-in cooling stand & interlocks	100k$	56k$	56
Clean Room Supplies	60k$	13k$	21
Miscellaneous Instrumentation	50k$	63k$	125
EDIA	378k$	166k$	44
Equipment Setup & Maintenance	110k$	93k$	85
Storage, test & shipping boxes	115k$	76k$	66
Transportation	102k$	204k$	200
Totals	**1,467k$**	**1,151k$**	**87%**

Total [redacted]

Item	Cost	Contingency	%
Module Production Labor	1,063 k$	457 k$	43%
Shell production & Rod assembly	126 k$	71 k$	56%
Equipment	1467 k$	1,151 k$	87%
Totals	**2,656** k$	**1,679** k$	**78%**

- Module Labor = 1,063 k$ + 457 k$ contingency = 1,520 k$
- Other Labor = 614 k$ + 330 k$ = 944 k$
  - Shell assembly = 126 k$ + 71 k$ = 197 k$
  - Eqpt. Setup and maintenance = 110 k$+ 93 k$ = 203 k$
  - EDIA = 378 k$ + 166 k$ = 544 k$
- Equipment Costs = 987 $ + 688k$ = 1,675 k$
- Transportation = 102 k$ +102 K$ = 204 k$

- TOTAL ESTIMATED COST 4.3 M$

- FNAL provides 0.5 M$

  $\Rightarrow$ need 3.8 M$ = 2.4 M$ base cost + contingency

Cost Estimati

- Production Rates
  - 80 pre-production over 5-6 months: goal to achieve steady rate of ~2 per day
  - 600 ramp-up over 6 months: goal is to go from ~2 to ~10 per day
  - 6000 production over 2 years: run at an average of ~12 per day
  - Contingent doubling of capacity: To sustain ~24 per day for 6 months

- Equipment Required
  - Probing: 1 automated probe stand (~50k$)
  - Assembly: Automated (211k$)
    - 2 automated pick-and-place "gantry" systems - one is mostly needed for contingency (~100k$ each)
    - Alternatively ~4 CMMs and ~12 fixtures (~20k$ each. SiDet has CMM's)
  - Inspection: Plan to inspect a fraction (~10%) of modules on OGP (at SiDet)

Cost Est[redacted]

- Wirebonding: (66k$ fixtures & MHS + 264K$ in contingency)
  - Need one K&S 8090 nearly full time, therefore need a second as contingency. (2 at SiDet)
  - If conflict with Run 2b, need to buy a 3rd K&S 8090. (250k$)
  - Will use the K&S Material Handling System (MHS ~50k$)
  - For Wirebonding we will need simple fixtures, possibly many of them (16k$)
- Testing equipment: (~30-40k$, total 225k$)
  - Need one system for quick tests in the clean room after wirebonding
  - Need separate systems for full tests: We'll multiplex and fully test many modules.
  - For Burn-in, we also need 1-2 DAQ stands
  - Some testing outside FNAL.

Cost Estimating

- Miscellaneous equipment-related expenses
  - Clean room supplies (2k$/month for 30 months = 60k$)
  - Burn-in cooling stands& interlocks (100k$)
  - Engineering, Design and Machining support (378k$)
    - 0.5 FTE machinist, 0.5 FTE engineer, 0.5 FTE designer for 30 months
  - Miscellaneous instrumentation for metrology, electronics testing (50K$)
  - Equipment setup and maintenance is covered by SiDet except CMS specific items: DAQ & Gantries (110k$)
  - Storage,test, and transportation boxes (115k$)

Cost Est

- Labor Costs for modules
    - 80 pre-production over 5-6 months: goal to achieve steady rate of ~2 per day
        - production labor cost 31k$
    - 600 ramp-up over 6 months: goal is to go from ~2 to ~10 per day
        - labor cost 119k$
    - 6000 production over 2 years: run at an average of ~12 per day
        - labor cost 913k$
  - Total production labor cost 1,063k$
    - Contingent 6 month doubling of capacity: Also include continuity of labor force.
  - Total contingency 457k$
- Labor Costs for assembly of TIB shell supports
  - 126k$ + 71k$ contingency

Conclusion

- CMS Tracker is now All-Silicon
- US CMS tracker group can play a significant role
  - Large scale production: more than 100 square meters
  - This is a seasoned, high quality group of physicists:
    - Significant experience not only in silicon production but also in tracking, pattern recognition, b tagging, and other aspects of hadron collider physics at the Tevatron
- Overall cost of production is 2.3M$
  - Less than 25k$ per square meter (a real bargain)
- We believe the tracker can be constructed on time

US CMS Silicon Tracker
Project Review

Aspen Meeting
Of the
Fermilab PAC

June, 2000

- CMS All Silicon Tracker
- Proposal for US CMS Tracker
- Project Management Appendices
    - Resource Loaded Schedule
    - Resource Sheet
    - Cost Breakdown
    - Cost Profile
    - Resource Usage Profile
    - Contingency Analysis

Table of Contents

1

Dan Green

US CMS Technical Director

Aspen PAC
June, 2000

Outline

- CMS decision to construct an all silicon tracker.
- Automation and radhard 0.25 μm IBM electronics.
- CMS tracker organization - community, horizontal work, and consortia.
- CMS cost and schedule.
- US CMS approved scope.
- US CMS proposed scope increase.

Tracker - CMS Status

- **The Status - Change to all-Si tracker** (subject to approval by the LHCC)
- Redesign offers opportunity to improve the structure, simplify the services, increase modularity and improve maintainability
- Results from mechanics prototypes built in 1999 can be exploited
- Exceptionally good results from APV25 f.e. electronics (0.25μm technology)
- Good progress with pixel detectors and electronics

- **Plans and milestones for 2000**
- Procurement Readiness Review in June (procurement of pre-production sensors)
- Establish automated module production in participating sites
- Systems tests in beam
- Study integration and maintenance scenarios
- Prototypes of final size pixel sensors

- **Concerns**
- Schedule: A detailed schedule has to be presented to the LHCC in May

Tracker Technology Decis

- Two stage Tracker in TDR (and MoU):
  low luminosity (Phase I)and high luminosity (Phase II)

- TDR approved with an important Milestone on MSGC robustness

- All silicon layout studied as alternative solution
  - low cost of Silicon sensors for large quantities in 6" technology
  - possibility of streamlining module assembly through automation

- Internal review in December 1999 to compare the two solutions on an equal footing.

Tracker Full Silicon

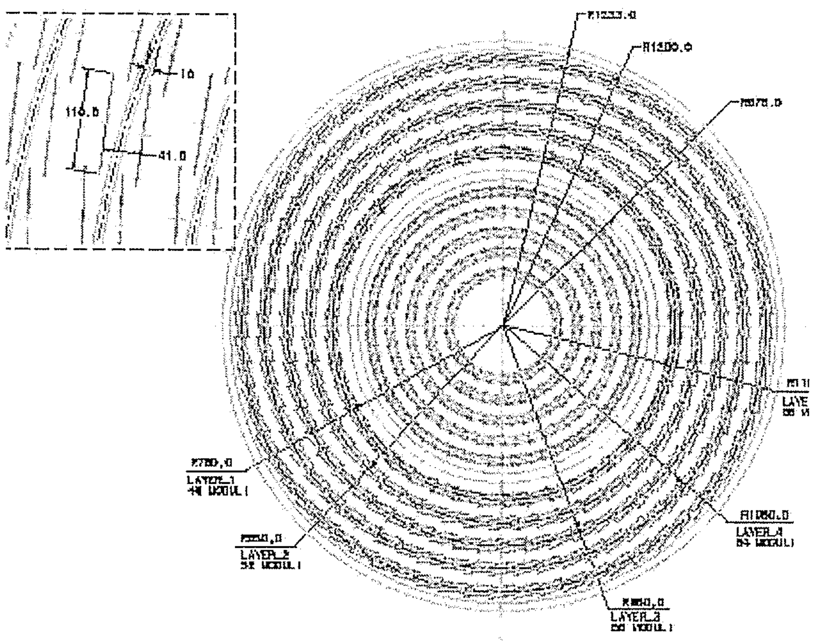
• The review showed that both solutions are technically feasible but highlighted the overall delay the project had incurred so far, raising concern about the collaboration to recover the lost time.

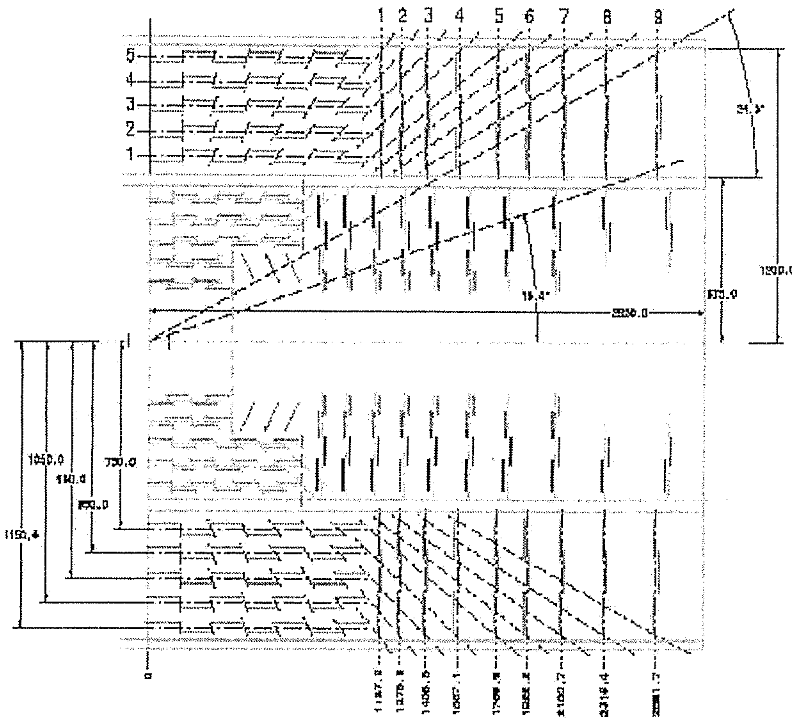
• Moving from two parallel technologies to a single one allows to concentrate all efforts onto a reduced set of problems

• For this reason CMS decided to propose a one stage **full Silicon Tracker**, with a performance similar to the one described in the TDR and within a cost ceiling of 77.5 MCHF.
(Addendum to CMS Tracker TDR presented to LHCC 8 March 2000)

• The Tracker community remains the same as before. The Project is being reorganized, taking advantage of a single detector technology. Construction tasks have been identified. Horizontal Projects corresponding to uniform solutions across the whole Tracker have been defined and distributed with clear Institution responsibilities. Module construction is shared between three Consortia.

CMS Silicon Tracker

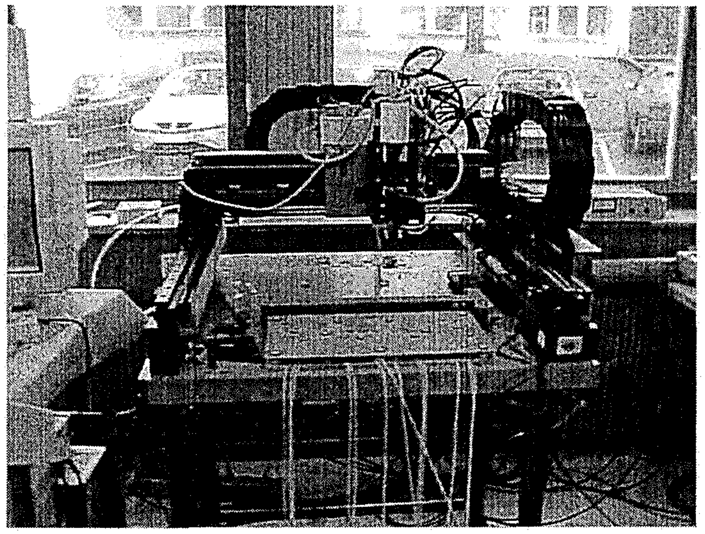


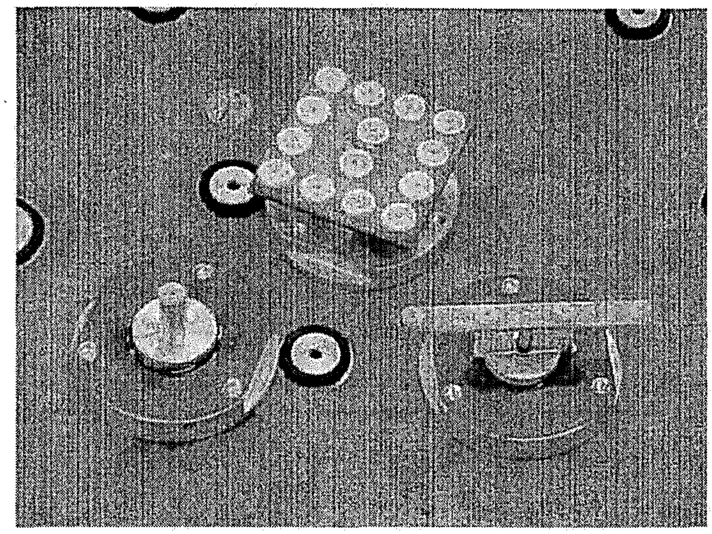


December 1999 - Decision to use silicon in the outer tracker.

- **10 barrel layers and 10 forward disks. Layers 1,2,5,6,7 and disks 1 and 10 are stereo/axial. All others axial only.**
- **Increase surface area from <100 m^2 to > 200 m^2**

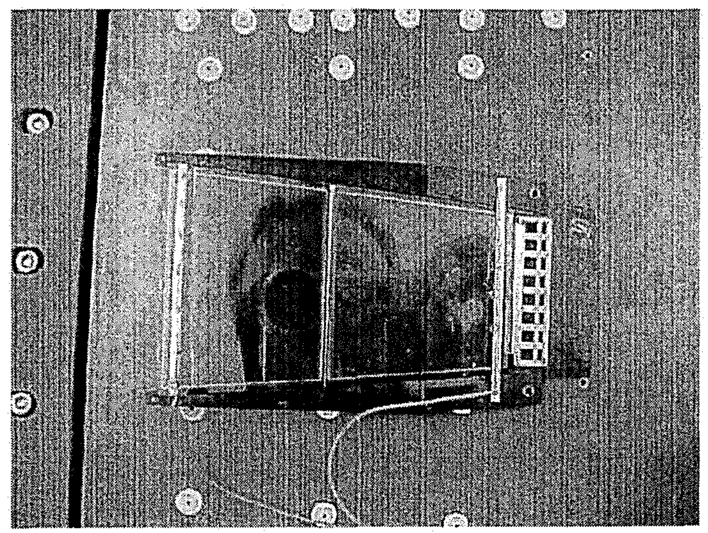
CMS Silicon Automat





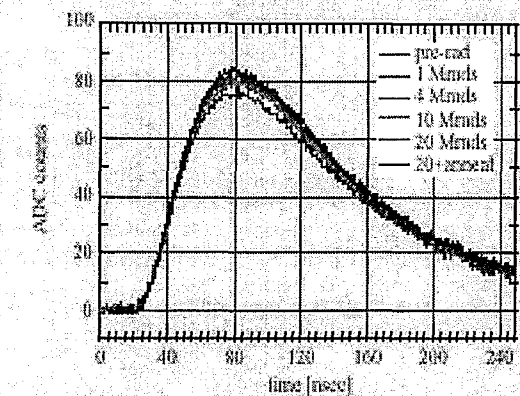
CERN Automatic pick-and-place

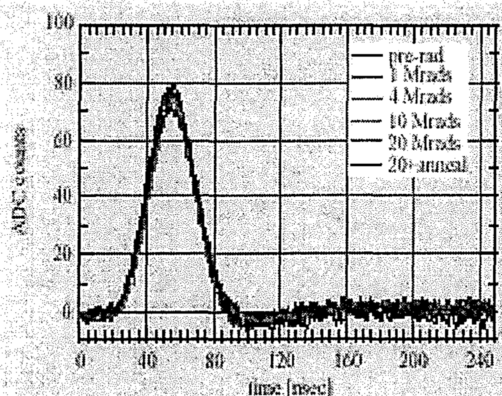
- Off the shelf hardware
- Vacuum pieces by CMS
- 2 technicians can assemble up to 4 modules per hour
- With 2 K&S 8090 wedge bonders a site can bond 4 modules per hour



Tracker - FE Electron

Pulse shapes in operation modes 0 - 20Mrad





S/N in Deconvolution Mode

Inner Silicon

Strip length 12.5 cm, t= 300 μm

S= 24000 - 15% (rad. dam.)

$N_{APV6} \approx 2000$ e $S/N_{APV6} \approx 10$

$N_{APV25} \approx 1600$ e $S/N_{APV25} \approx 13$

Outer Silicon

Strip length 16.5 cm, t= 400 μm

S= 31000 - 15% (rad. dam.)

$N_{APV25} \approx 1850$ e $S/N_{APV25} \approx 14$

Other parameters:

linearity
cross-talk
stability
uniformity

all excellent

Yield is high & chip smaller
=> lower cost

Power reduced
=> system gain

Buffers longer
=> no T1 risk

Tracker Community

47 Institutions from 11 Countries with > 500 Physicists & Engineers

Austria Wien
Belgium Antwerpen Univ., ULB Brussels, VUB Brussels, Louvain-La-
Neuve Univ., Mons Univ.
CERN CERN
Estonia Tallinn
Finland Helsinki Inst. of Phys., Helsinki Univ., Helsinki Univ. of Techn.,
Jyvaskyla Univ., Oulu Univ.
France Lyon I Univ., UHA Mulhouse, IReS / LEPSI Strasbourg
Germany RWTH I Aachen, RWTH IIIB Aachen, Berlin Univ., Karlsruhe
India Panjab Univ., Tata Institute EHEP, Tata Institute HECR
Italy Bari Univ. & INFN, Catania Univ. & INFN, Firenze Univ. & INFN,
Padova Univ. & INFN, Perugia Univ. & INFN, Pisa Univ. & INFN,
Torino Univ. & INFN
Switzerland Basel Univ., ETH Zürich, PSI, Zürich Univ.
U.K. Brunel Univ., Imperial College, RAL
USA UC Davis, Fermilab, Florida Univ., Johns Hopkins Univ.,
Mississippi Univ., Northwestern Univ., Purdue Univ., Rochester Univ.,
Rutgers Univ., TexasTech Univ.

Tracker Horizontal Proj...

project:	responsibility:	help from:
R.O. hybrids	Strasbourg	Aachen+others to bond hybrid to pitch adapter
Opto-hybrids	Perugia	
Pitch adapters	Belgium	
Sensor testing	Pisa&Karlsruhe	Louvain, Perugia,
Strasbourg		
Frames	Belgium&Strasbourg	
FE chips	UK	Padova (if needed)
Glue chips	CERN	
Optical link	CERN	
Power supplies	Florence	Torino
Cables&connect.	Bari&others	
Control system	CERN	Karlsruhe, Wien
Elect. Integrat.	CERN	All
Mechanics Integr. &cooling,cabling, services+external infrastructure	CERN	

Tracker Module Construct

~ 19000 single sided equivalent modules shared in three Consortia:

CE: Austria, Belgium, Germany, Finland, France, Switzerland
INFN: Bari, Catania, Firenze, Padova, Perugia, Pisa, Torino
USA: Fermilab, Purdue, Rochester, Northwestern

☞ Centralize the production as much as possible:

- ❒ Assembly robots
  - ➢ Brussels, Lyon
  - ➢ Bari, Perugia
  - ➢ Fermilab (2)
- ❒ Bonding machines
  - ➢ Aachen, Karlsruhe, Strasbourg, Zurich
  - ➢ Bari, Florence, Padova, Pisa, Torino
  - ➢ Fermilab
- ❒ Wien & Finland, each produces 2.5% of modules with semiautomatic mounting

Tracker Mechanics and Integ...

Mechanics

❒ Overall Support Structure	CERN
❒ Outer Barrel	CERN/Finland
❒ Inner Barrel	Pisa/Fermilab
❒ Forward Disks	Aachen

Module Integration on the Structures

➢ Outer Barrel	CERN/Finland + INFN
➢ Inner Barrel	Pisa
➢ Forward Disks	CE + CERN

Tracker Cost and Fund

COST estimate to be reviewed by the LHCC Cost Review Committee (CORE)

	Total	Barrel	Forward
Pixel	8.24	5.77	2.47
Inner Silicon	21.71	11.45	10.26
Outer Silicon	38.21	23.12	15.09
General Mechanics	9.42		
Total Cost	**77.58 MCHF**		

(MoU PhI tracker 74.0 MCHF)

Funding and MoU

Amendment to MoU concerning the new Tracker sharing of responsibility and funding in preparation.

Draft Amendment for October RRB, aiming at approval for April 2001 RRB.

Tracker Construction Sche

Feb. 21	Submission of the Addendum to LHCC
8 March	Open presentation of the Addendum
23 March	Workshop on Tracker Layout
17 April	TK Week: schedule & milestones for construction
18 May	Possibly approval by LHCC
15 June	Project Readiness Review on sensors (order a pre-series of final sensors)
1st July	Start the tender on sensors
October	End of the tender on sensors. Draft amendment to MoU for RRB
November	Engineering Design Review and Annual Tracker Review
End 2000	Start the Tracker construction with a pre-series of final modules
April 2001	RRB approval amendment to MoU

US CMS Silicon Tracker

B. Flaugher, C. Gerber, J. Goldstein, J. Incandela, M. Kubantsev, R. Lipton, P. Lukens, S. Mishra, T. Nelson, P. Rapidis, L. Spiegel, D. Stuart, S.Tkaczyk
Fermi National Accelerator Laboratory

T. Bolton, R. Demina, W. Reay, R. Sidwell, N. Stanton
*Kansas State University**

D. Buchholz
Northwestern University

I. Shipsey, D. Miller
Purdue University

A. Bean, P. Baringer
*Universtiy of Kansas**

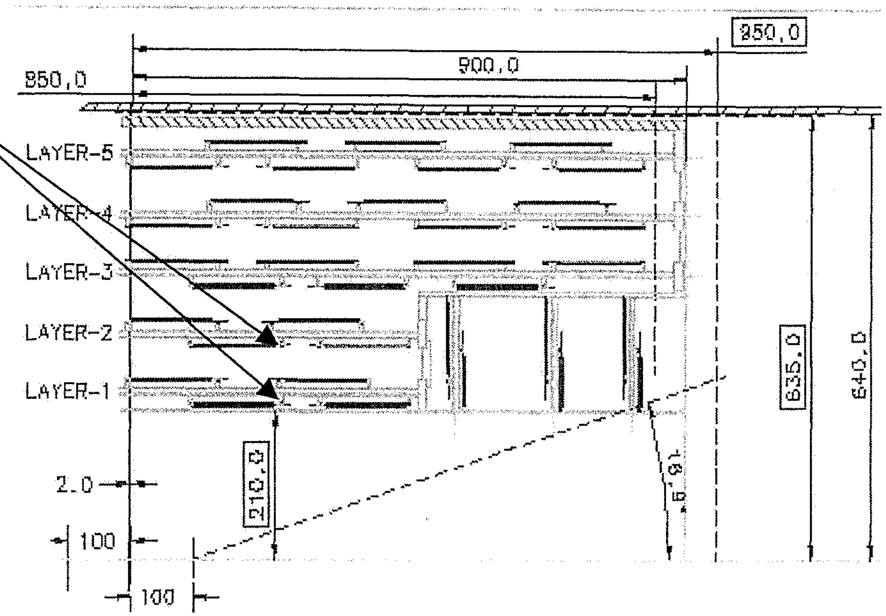
S. Blusk, M. Kruse, P. Tipton
University of Rochester

** New group*

US CMS Approved S

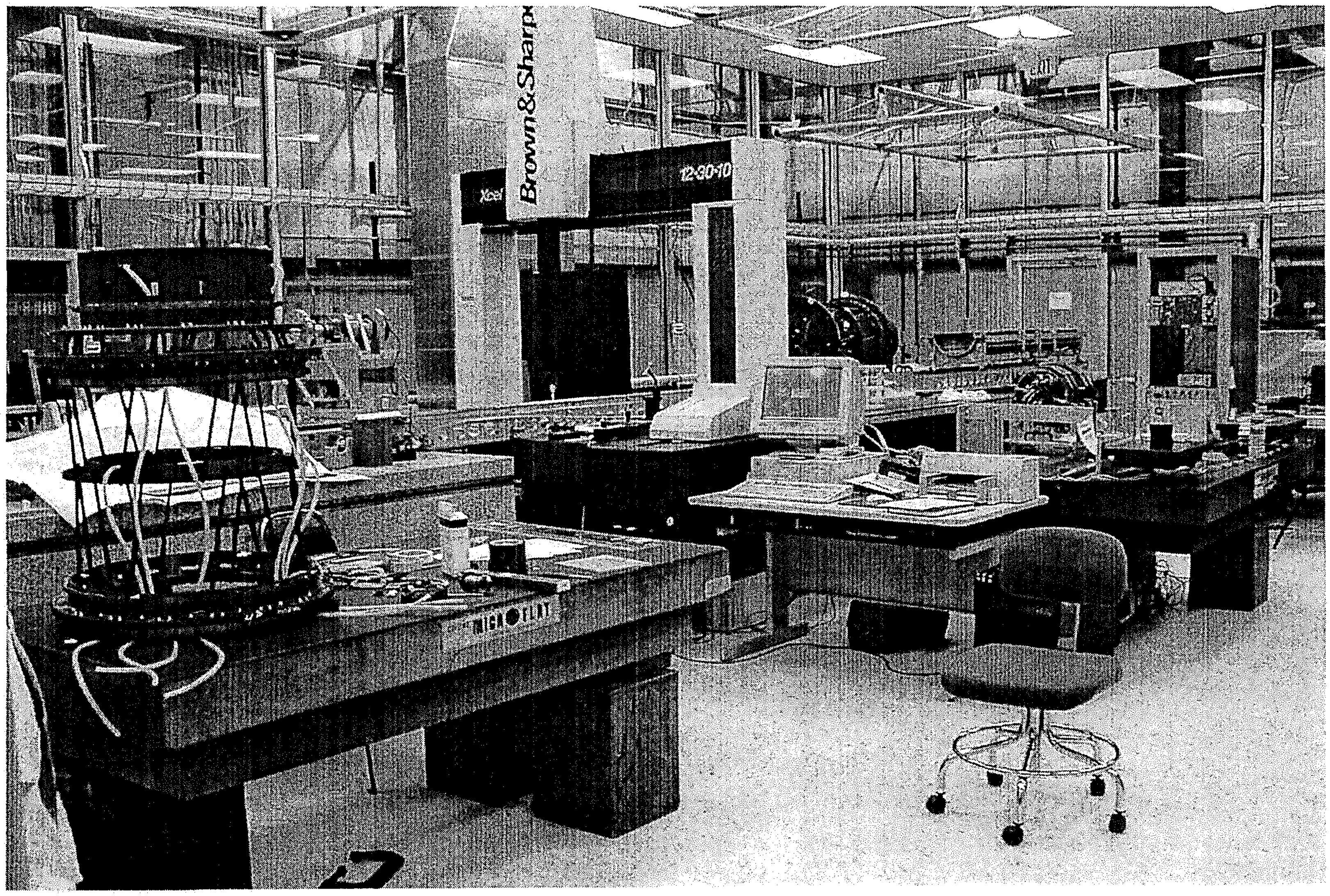
Innermost 2 layers of barrel.

- **Precision fabrication and testing of ~1000 single-sided-equivalent silicon micro-strip modules.**
- **Assembly of half-cylinder supports for inner two layers**
- **Installation of modules on support cylinders**
- **Transportation of completed half-cylinders to CERN.**



In November of 1999, US CMS submitted a Change Request to the Fermilab PMG to increase the scope of US CMS at no cost to the Project. After a review, this CR was approved.

SiDet - Space & Equipme



US CMS - Increased Sco

6000 outer barrel modules (107 m^2 of silicon):

- Silicon area 16.5 cm x 10.8 cm
- 2 single-sided sensors w/ active area ~8.0 cm x 10.75 cm
- 140 μm pitch$\Rightarrow$ 768 channels $\Rightarrow$ 6 chips $\Rightarrow$ 3,204 bonds

- **By comparison, consider CDF ISL half-ladder**
  - Silicon area per side ~ 6 cm x 21 cm
  - 3 double sided sensors w/ active area ~5.8 cm x 6.8 cm
  - 112 μm pitch$\Rightarrow$ 1024 channels $\Rightarrow$ 8 chips $\Rightarrow$ 4,084 bonds
- **CMS modules are simpler**
  - 75% of the alignment, assembly, and wirebonding steps
  - 50% of setup time.

Support cylinders

- **Already plan on inner two layers of inner barrel**
- **Well also do a larger radius inner barrel layer**

WBS 8
Silicon Tracking Layers

8.1 Findings and Comments

The silicon tracker so far committed to involves the inner two layers and entails the assembly of 1000 single-sided equivalent detector modules from components supplied by International CMS. The module design and assembly procedures are very similar to those employed in the CDF ISL, and the scale of the project is estimated to be about 6-10% of the CDF scale.

> **Comments:** This project makes excellent use of the experience and resources built up over many years of CDF construction. Being single sided silicon, it is intrinsically simpler than the CDF ISL, and should require only a small fraction of the capacity of the SiDet facility. The principle point of concern is the exposure coming from the fact that the project has no control over that arrival schedule of parts from International CMS. Otherwise this project looks in good shape.

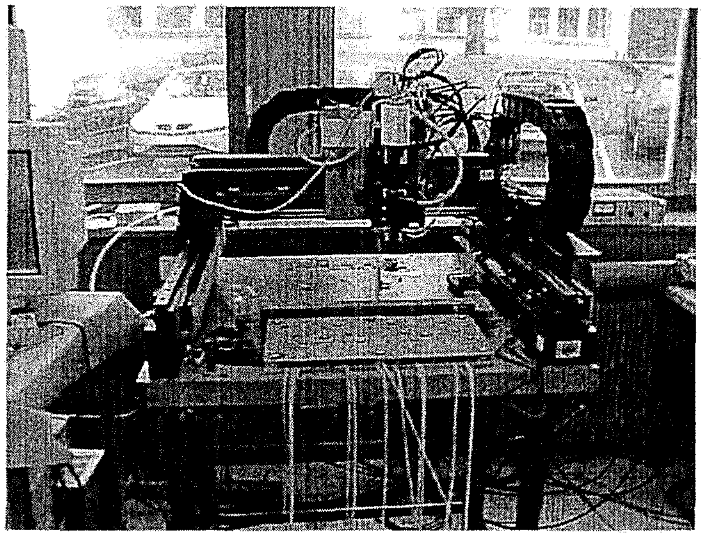
A proposal to extend the scope of the SiTrk project to include a large part of the newly siliconized outer tracker is not formally part of this review, but was heard by the committee. This extension entails more assembly of single sided silicon units, increasing the number from 1000 equivalents to 7000. SiDet facilities would be required at about the 50% level. Two schemes, one manual, one robotic, have been investigated as possible ways to accomplish this task, and both are feasible, with little cost difference between them.

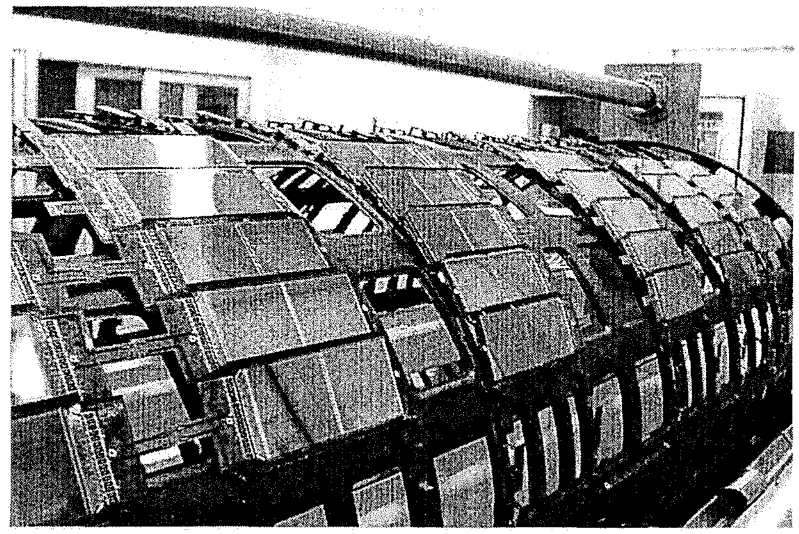
> **Comments:** Despite the daunting number of modules to be assembled, the committee is persuaded that the design has been streamlined to a point where this is easily possible in the two year timetable presented. As with the two-layer silicon project, this one too has no control over the arrival of parts from International CMS. The robotic solution is probably less sensitive to variations in the parts arrival schedule. Spin off benefits to the SiDet facility and future silicon efforts at FNAL are evident.

Recommendations:

1. Establish with International CMS a clear schedule of sensor deliveries by July 1st.

US CMS - Benefits to FN





- Automation in the construction of CDF and D∅ replacements for Run 2b (necessitated by Run 2a Radiation Damage).
- The technology of single-sided modules with Carbon Fiber support cylinders would enable low cost, low risk replacements of CDF or D∅ tracking elements for very high luminosity operation.

Summary

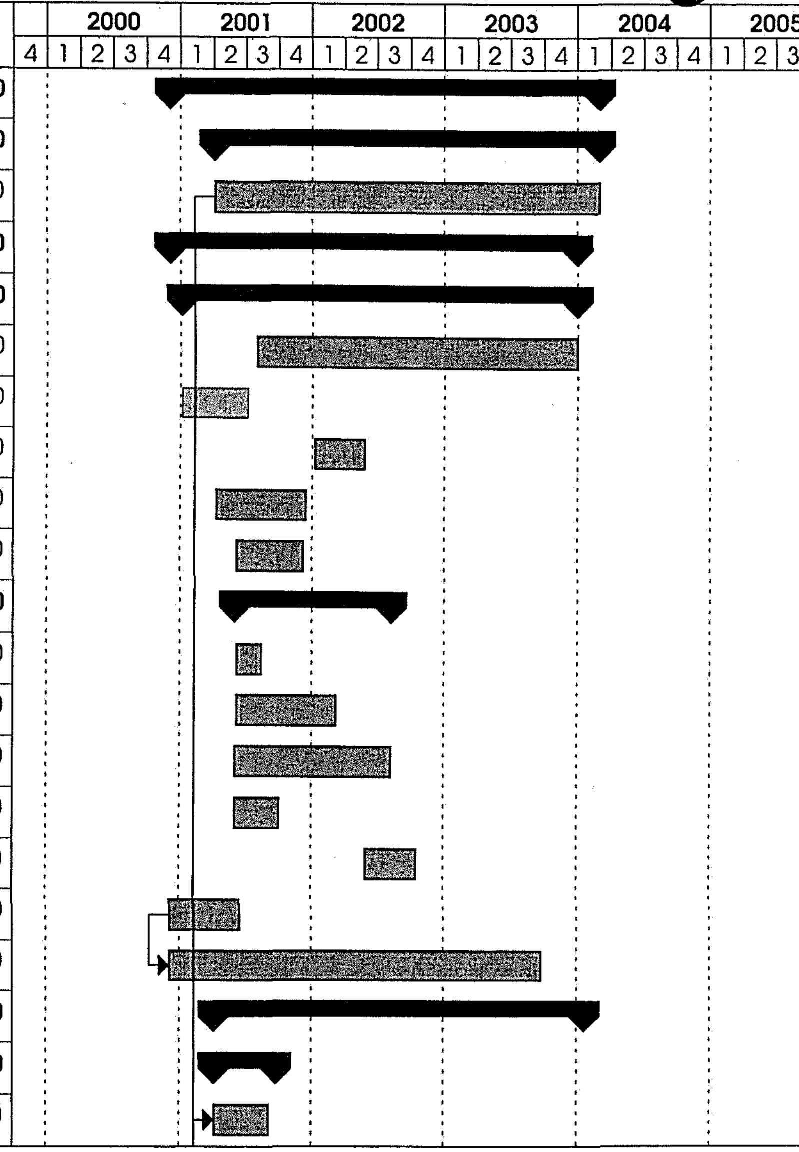
- The need to confront LHC Physics well at CMS drives the decision for an all silicon tracker.
- US CMS physicists have a strong team for silicon tracking. They have experience which is crucial to the success of CMS both in Si construction and operation and in reconstruction and analysis.
- Therefore, US CMS proposes to take a major role in CMS tracking as a large extension of the approved project scope.
- By investing in automation and training the SiDet staff, US CMS will make a positive impact on FNAL experiments, notably CDF and D0 in Run IIb.

2

3

4

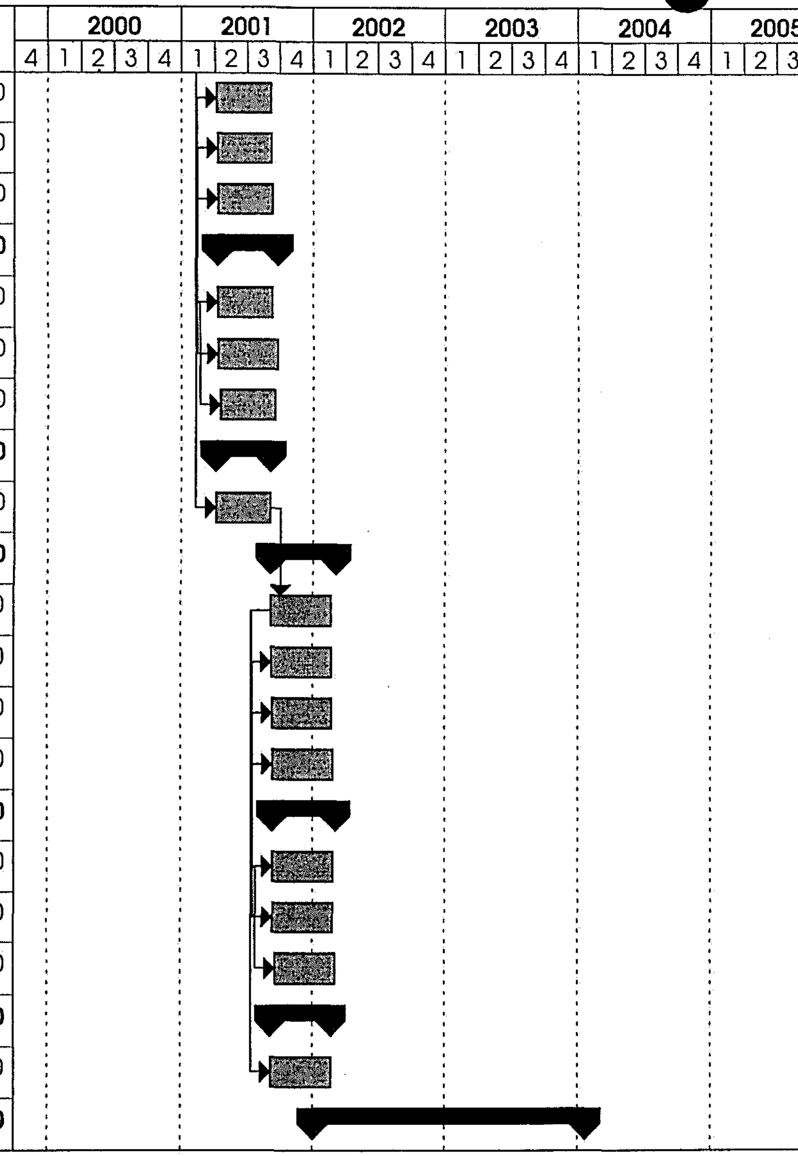
ID	WBS	Task Name	Cost
1	**8**	**US CMS Tracker Project**	**$2,655,740.20**
2	**8.1**	**Components**	**$60,000.00**
3	8.1.2	miscellaneous clean room materials	$60,000.00
4	**8.2**	**Equipment**	**$1,304,083.80**
5	**8.2.1**	**Mechanical Assembly Equipment**	**$588,701.80**
6	8.2.1.1	Machined parts	$377,701.80
7	8.2.1.2	Automation equipment	$211,000.00
8	8.2.2	Wirebonding Machinery	$66,000.00
9	8.2.3	Electronic Test	$225,000.00
10	8.2.4	Burn-in Cooling/test systems	$100,000.00
11	**8.2.5**	**Boxes**	**$115,000.00**
12	8.2.5.1	Storage	$35,000.00
13	8.2.5.2	Transportation boxes	$30,000.00
14	8.2.5.3	Test Boxes	$50,000.00
15	8.2.6	Probe-station	$50,000.00
16	8.2.7	Miscellaneous instrumentation	$50,000.00
17	8.2.8	Equipment setup	$55,874.00
18	8.2.9	Equipment maintenance	$53,508.00
19	**8.3**	**Modules**	**$1,063,544.40**
20	**8.3.1**	**preproduction of 80 modules**	**$31,337.20**
21	8.3.1.1	Mechanical Assembly	$17,578.00



Project: US CMS Silicon Tracker
Date: Thu 06/01/00

Task
Progress
Milestone
Summary
Rolled Up Task
Rolled Up Milestone
Rolled Up Progress
Split
External Tasks
Project Summary

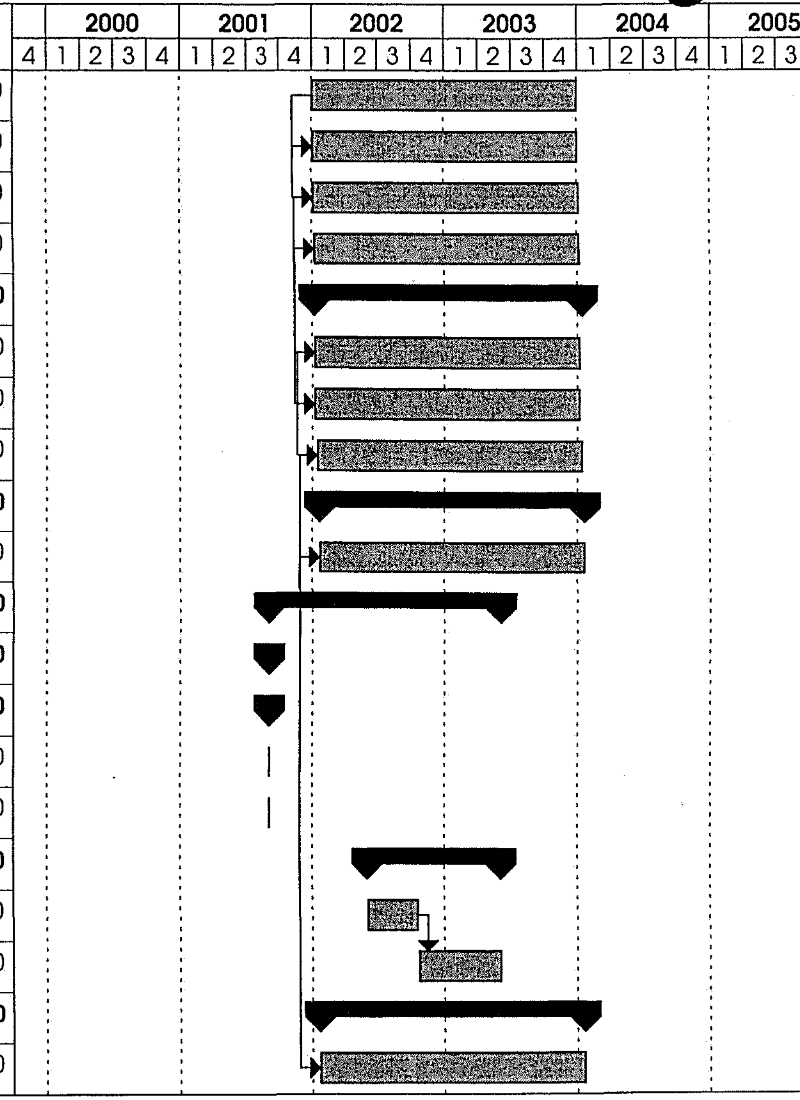
ID	WBS	Task Name	Cost
22	8.3.1.2	Wirebonding	$4,804.80
23	8.3.1.3	Inspection	$2,402.40
24	8.3.1.4	Repair	$0.00
25	8.3.1.5	**Testing, rod assembly & burn-in**	**$6,552.00**
26	8.3.1.5.1	Full electronic test	$0.00
27	8.3.1.5.2	rod assembly	$6,552.00
28	8.3.1.5.3	burn-in	$0.00
29	8.3.1.6	**Documentation**	**$0.00**
30	8.3.1.6.1	Assembly, Test, Ship/receive	$0.00
31	**8.3.2**	**Assembly of 600 modules: ramp-up**	**$119,467.20**
32	8.3.2.1	Mechanical Assembly	$57,528.00
33	8.3.2.2	Wirebonding	$26,208.00
34	8.3.2.3	Inspection	$5,241.60
35	8.3.2.4	Repair	$5,241.60
36	8.3.2.5	**Testing**	**'$13,104.00**
37	8.3.2.5.1	Full electronic test	$0.00
38	8.3.2.5.2	rod assembly	$13,104.00
39	8.3.2.5.3	burn-in	$0.00
40	8.3.2.6	**Documentation**	**$12,144.00**
41	8.3.2.6.1	Assembly, Test, Ship/receive	$12,144.00
42	**8.3.3**	**Assembly of 6000 modules**	**$912,740.00**



Project: US CMS Silicon Tracker
Date: Thu 06/01/00

Task
Progress
Milestone
Summary
Rolled Up Task
Rolled Up Milestone
Rolled Up Progress
Split
External Tasks
Project Summary

ID	WBS	Task Name	Cost
43	8.3.3.1	Mechanical Assembly	$239,700.00
44	8.3.3.2	Wirebonding	$273,000.00
45	8.3.3.3	Inspection	$21,840.00
46	8.3.3.4	Repair	$54,600.00
47	8.3.3.5	**Testing**	**$273,000.00**
48	8.3.3.5.1	Full electronic test	$109,200.00
49	8.3.3.5.2	rod assembly	$54,600.00
50	8.3.3.5.3	burn-in	$109,200.00
51	8.3.3.6	**Documentation**	**$50,600.00**
52	8.3.3.6.1	Assembly, Test, Ship/receive	$50,600.00
53	**8.4**	**Support Structures**	**$126,112.00**
54	**8.4.1**	**Equipment**	**$0.00**
55	**8.4.1.1**	**Support Cylinder Gluing Jigs**	**$0.00**
56	8.4.1.1.1	Ribbon and Cooling Tube Jig	$0.00
57	8.4.1.1.2	Precision ledge placement jig	$0.00
58	**8.4.2**	**Assembly**	**$126,112.00**
59	8.4.2.1	Attachment of cooling tubes and ribbons	$47,908.00
60	8.4.2.2	Attachment of precision positioning ledges	$78,204.00
61	**8.5**	**Transportation**	**$102,000.00**
62	8.5.1	Shipments to CERN	$102,000.00



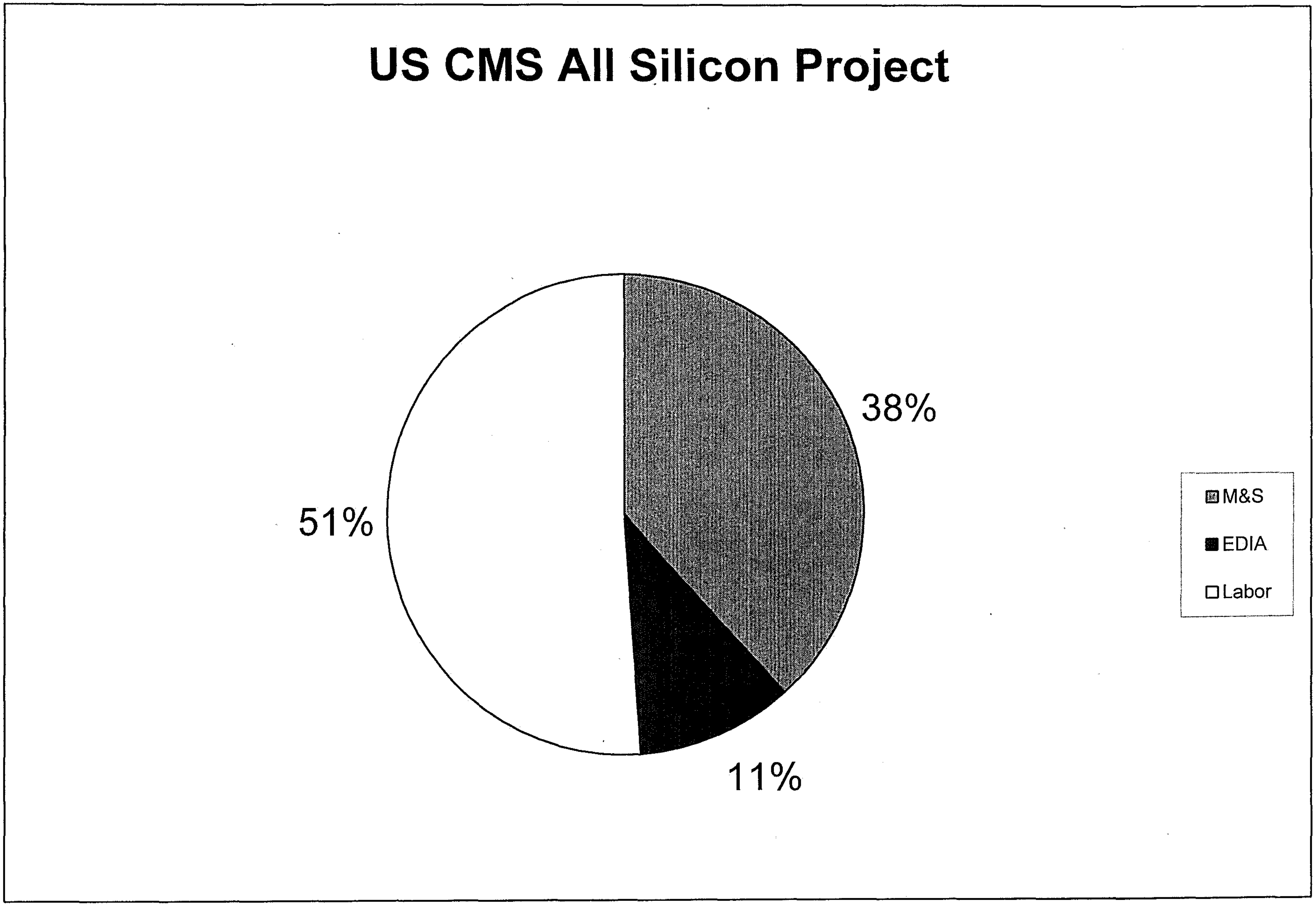
Project: US CMS Silicon Tracker
Date: Thu 06/01/00

Task		Rolled Up Task		External Tasks	
Progress		Rolled Up Milestone		Project Summary	
Milestone		Rolled Up Progress			
Summary		Split			

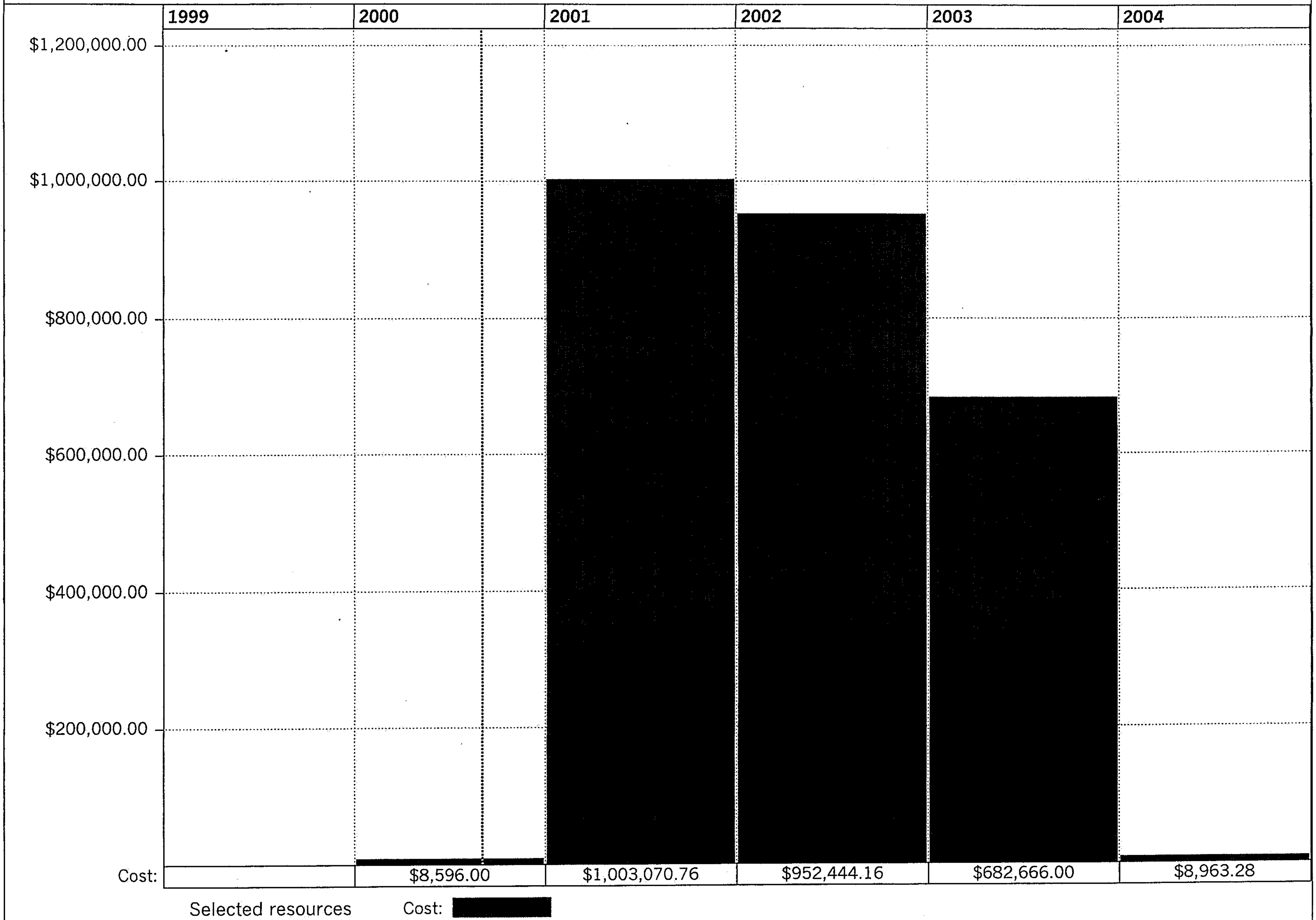
5

ID	Resource Name	Std. Rate	Cost Per Use	Work	Peak	Res. Type	Funding
1	**physicist**	**$0.00/day**	**$0.00**	**5,168.4 days**	**1,510%**		
2	**post-doc**	**$0.00/day**	**$0.00**	**60.9 days**	**10%**		
3	computer professional - fermi	$422.80/day	$0.00	0 days	0%		
4	**engineer - fermilab**	**$422.80/day**	**$0.00**	**409.5 days**	**70%**		
5	guest engineer - fermilab	$384.00/day	$0.00	0 days	0%		
6	**designer - fermilab**	**$370.40/day**	**$0.00**	**304.5 days**	**50%**		
7	drafter - fermilab	$289.20/day	$0.00	0 days	0%		
8	**machinist - fermilab**	**$447.20/day**	**$0.00**	**304.5 days**	**50%**		
9	**technician specialist - fermil**	**$218.40/day**	**$0.00**	**256 days**	**110%**		
10	**technician - fermilab**	**$218.40/day**	**$0.00**	**4,745 days**	**1,095%**		
11	guest technician - fermilab	$168.00/day	$0.00	0 days	0%		
12	**temp or student - fermilab**	**$101.20/day**	**$0.00**	**1,605 days**	**500%**		
13	engineer - university	$300.00/day	$0.00	0 days	0%		
14	technician - university	$120.00/day	$0.00	0 days	0%		
15	machinist - university	$140.00/day	$0.00	0 days	0%		
16	temp or student- university	$80.00/day	$0.00	0 days	0%		
17	Wirebonder M.H.S.	$0.00/hr	$50,000.00	90 days	100%		
18	**Wirebond fixture**	**$0.00/hr**	**$2,000.00**	**720 days**	**800%**		
19	Wirebonder	$0.00/hr	$250,000.00	0 days	0%		
20	**APV Test stand**	**$0.00/hr**	**$75,000.00**	**360 days**	**200%**		
21	APV Burn-in stand	$0.00/hr	$75,000.00	180 days	100%		
22	**dry box**	**$0.00/hr**	**$1,000.00**	**1,800 days**	**3,500%**		
23	**Pick and place setup**	**$0.00/hr**	**$105,500.00**	**240 days**	**200%**		
24	**Monthly materials**	**$0.00/hr**	**$2,000.00**	**22,080 days**	**3,000%**		
25	**Burn-in Cooling stand**	**$0.00/hr**	**$50,000.00**	**270 days**	**200%**		
26	**Tansportation Box**	**$0.00/hr**	**$5,000.00**	**1,200 days**	**600%**		
27	**200 Modules transport**	**$0.00/hr**	**$6,000.00**	**8,500 days**	**1,700%**		
28	Probe Station	$0.00/hr	$50,000.00	90 days	100%		
29	**Test boxes**	**$0.00/hr**	**$250.00**	**60,000 days**	**20,000%**		
30	Miscellaneous Instrumentatio	$0.00/hr	$50,000.00	100 days	100%		

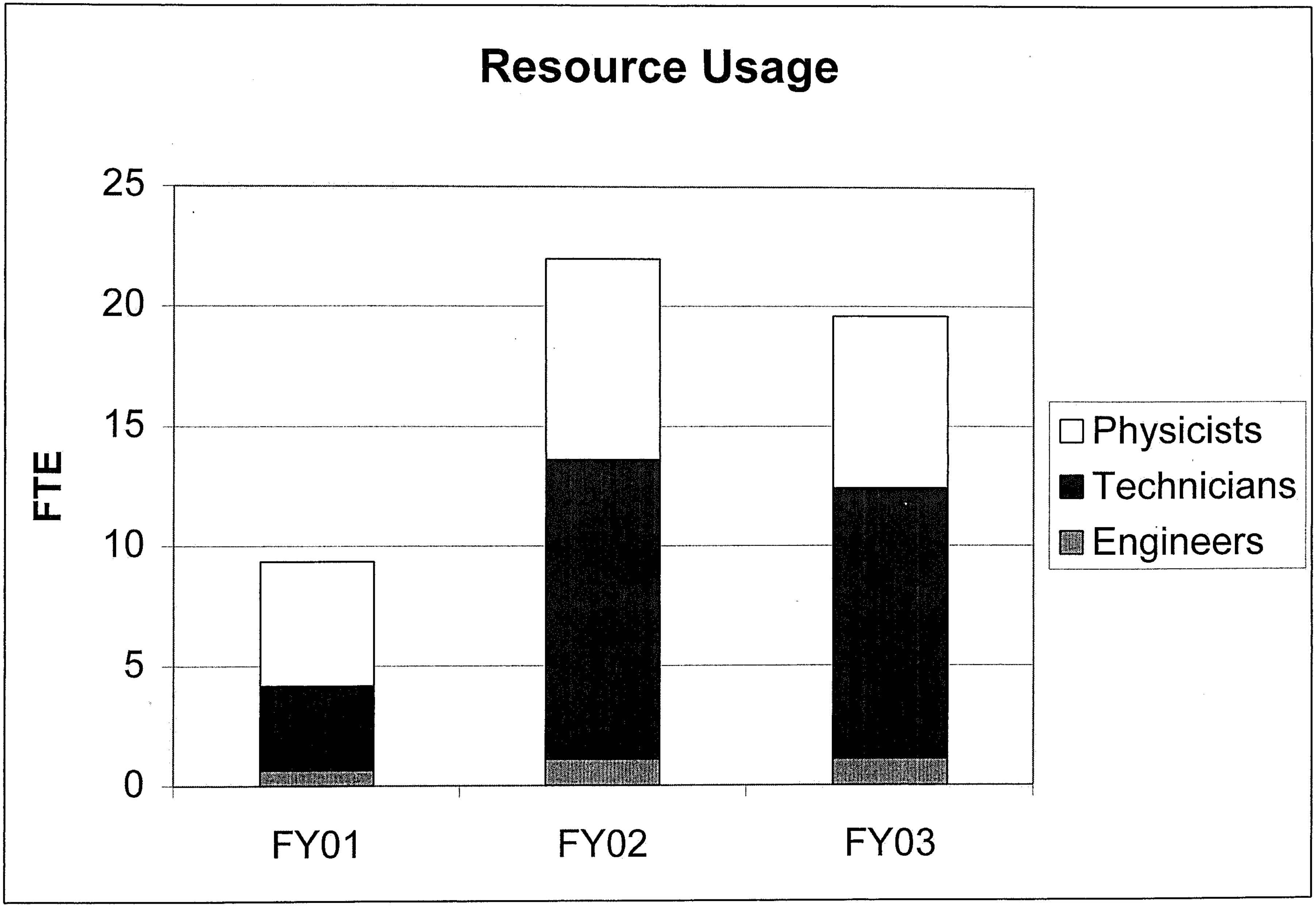
6


US CMS All Silicon Project
38%
51%
11%
M&S
EDIA
Labor

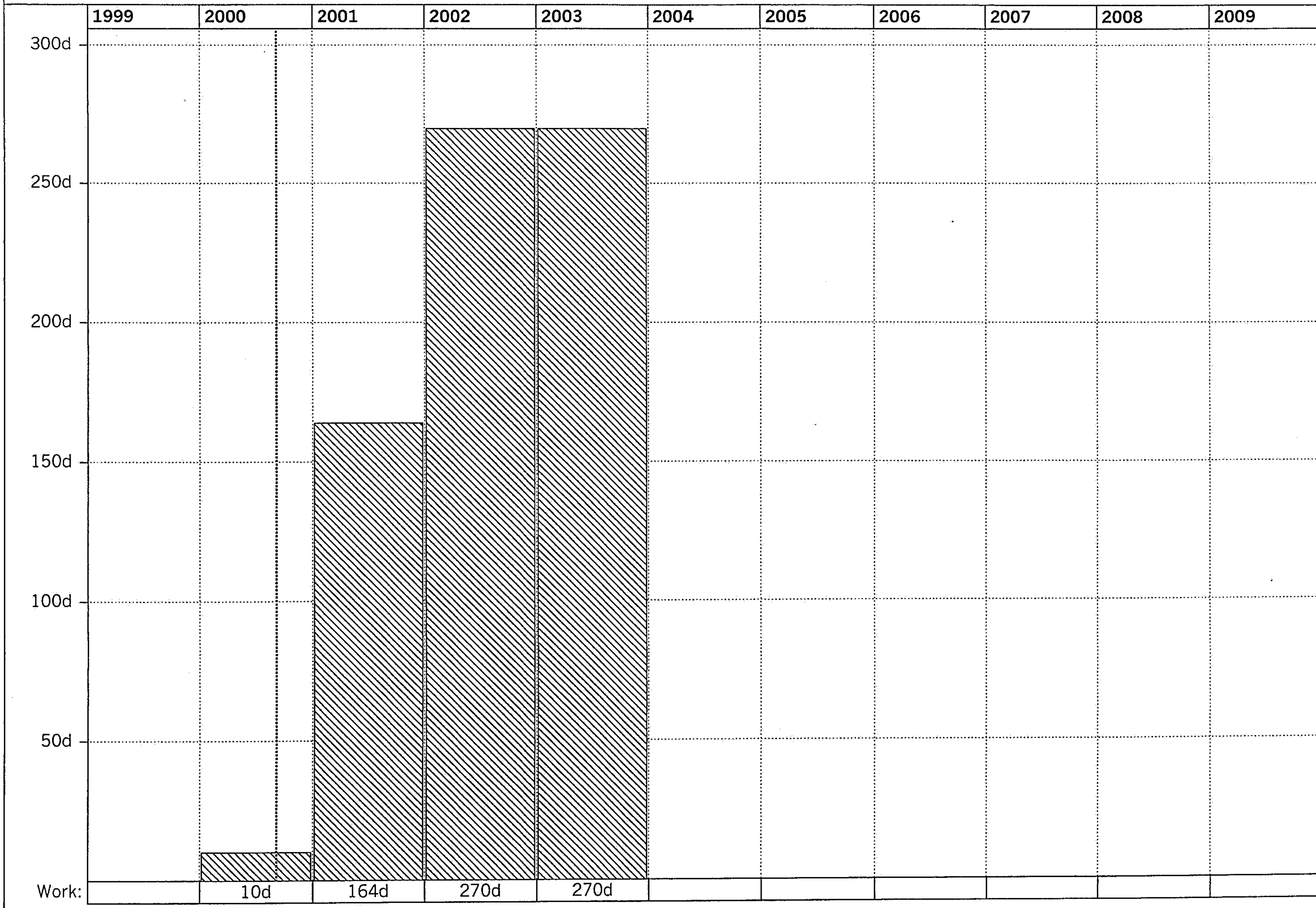
7


1999
2000
2001
2002
2003
2004
$1,200,000.00
$1,000,000.00
$800,000.00
$600,000.00
$400,000.00
$200,000.00
Cost:
$8,596.00
$1,003,070.76
$952,444.16
$682,666.00
$8,963.28
Selected resources
Cost:

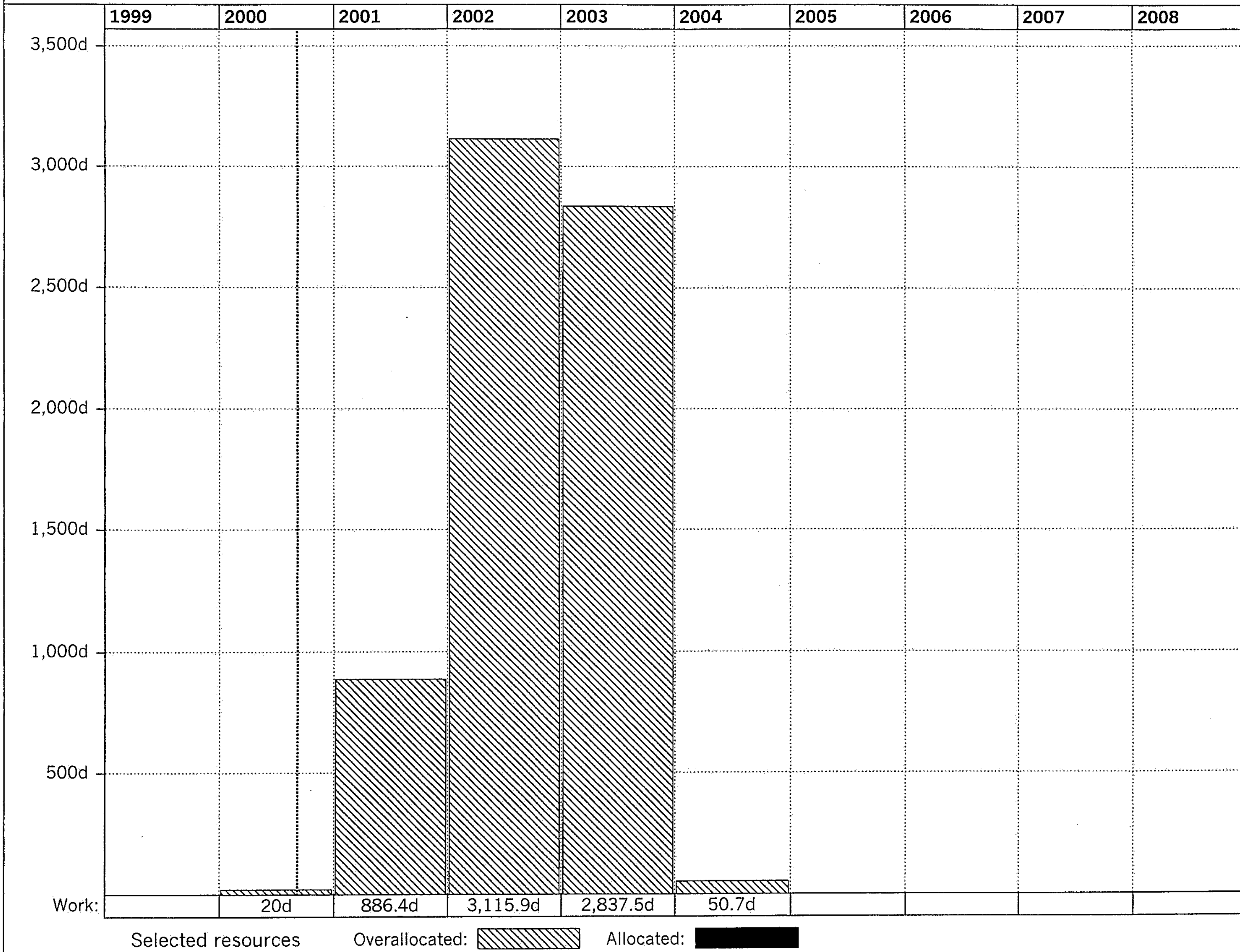
8

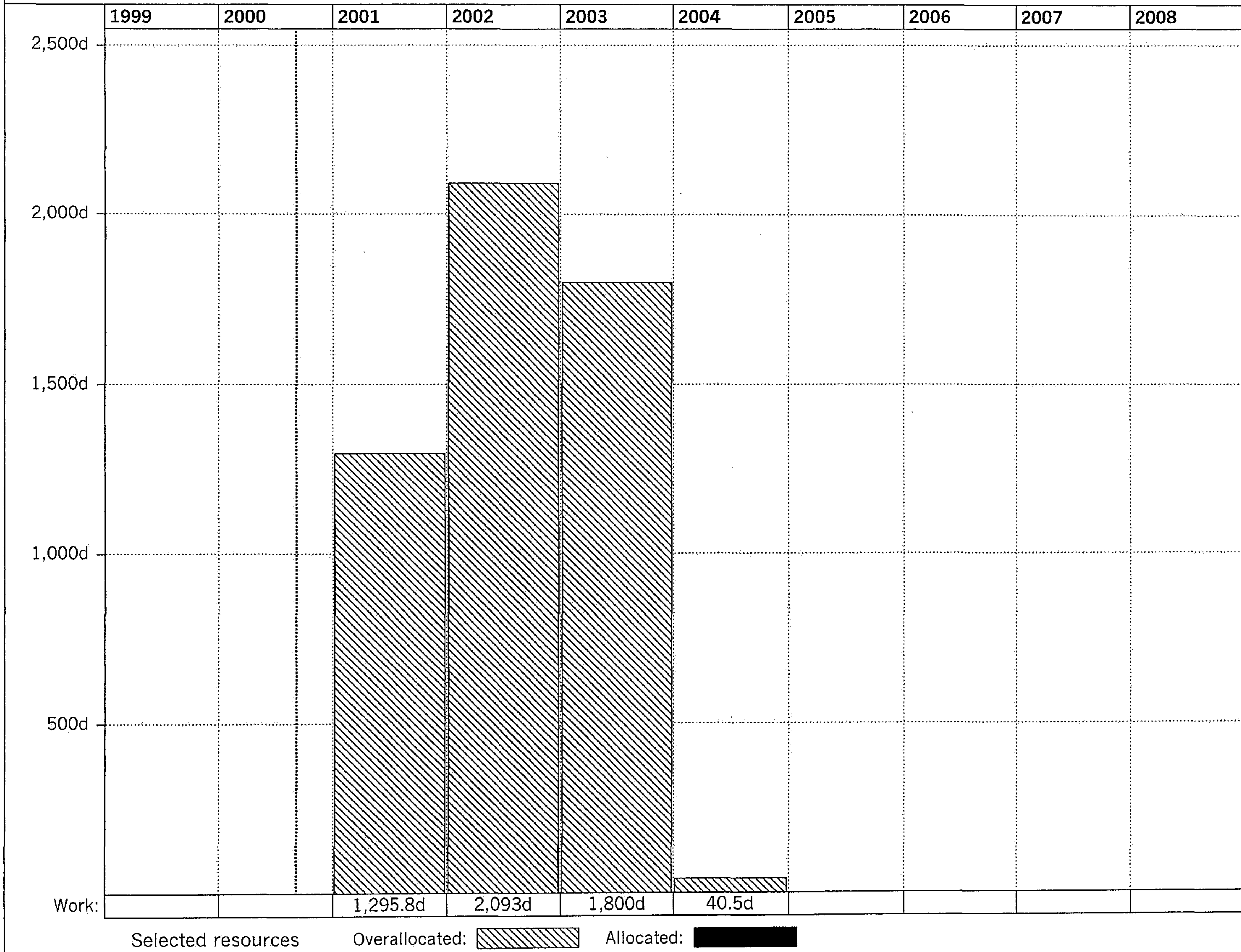


Resource Usage
FTE
25
20
15
10
5
0
FY01
FY02
FY03
Physicists
Technicians
Engineers



Selected resources Overallocated: Allocated:


1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
3,500d
3,000d
2,500d
2,000d
1,500d
1,000d
500d
Work:
20d
886.4d
3,115.9d
2,837.5d
50.7d
Selected resources
Overallocated:
Allocated:


1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2,500d
2,000d
1,500d
1,000d
500d
Work:
1,295.8d
2,093d
1,800d
40.5d
Selected resources
Overallocated:
Allocated:

9

Contingency Estimate

WBS	Task	N1	N2	Base	Total	Contingency	%
8	**US CMS Tracker Project**	**0**	**0**	**$2,655,740.20**	**$4,334,431.82**	**$1,678,691.62**	**63.2%**
8.1	Components	0	0	$60,000.00			
8.1.2	miscellaneous clean room materials	1.1	1.1	$60,000.00	**$72,600.00**	**$12,600.00**	**21.0%**
8.2	Equipment	0	0	$1,304,083.80			
8.2.1	Mechanical Assembly Equipment	0	0	$588,701.80			
8.2.1.1	Machined parts	1.2	1.2	$377,701.80	**$543,890.59**	**$166,188.79**	**44.0%**
8.2.1.2	Automation equipment	1.1	1.2	$211,000.00	**$278,520.00**	**$67,520.00**	**32.0%**
8.2.2	Wirebonding Machinery	1	5	$66,000.00	**$330,000.00**	**$264,000.00**	**400.0%**
8.2.3	Electronic Test	1.2	1.3	$225,000.00	**$351,000.00**	**$126,000.00**	**56.0%**
8.2.4	Burn-in Cooling/test systems	1.2	1.3	$100,000.00	**$156,000.00**	**$56,000.00**	**56.0%**
8.2.5	Boxes	0	0	$115,000.00			
8.2.5.1	Storage	1.5	1.5	$35,000.00	**$78,750.00**	**$43,750.00**	**125.0%**
8.2.5.2	Transportation boxes	1.2	1.3	$30,000.00	**$46,800.00**	**$16,800.00**	**56.0%**
8.2.5.3	Test Boxes	1.1	1.2	$50,000.00	**$66,000.00**	**$16,000.00**	**32.0%**
8.2.6	Probe-station	1.2	1.2	$50,000.00	**$72,000.00**	**$22,000.00**	**44.0%**
8.2.7	Miscellaneous instrumentation	1.5	1.5	$50,000.00	**$112,500.00**	**$62,500.00**	**125.0%**
8.2.8	Equipment setup	1.5	1.5	$55,874.00	**$125,716.50**	**$69,842.50**	**125.0%**
8.2.9	Equipment maintenance	1.2	1.2	$53,508.00	**$77,051.52**	**$23,543.52**	**44.0%**
8.3	Modules	0	0	$1,063,544.40			
8.3.1	preproduction of 80 modules	0	0	$31,337.20			
8.3.1.1	Mechanical Assembly	1.1	1.3	$17,578.00	**$25,136.54**	**$7,558.54**	**43.0%**
8.3.1.2	Wirebonding	1.1	1.3	$4,804.80	**$6,870.86**	**$2,066.06**	**43.0%**
8.3.1.3	Inspection	1.1	1.3	$2,402.40	**$3,435.43**	**$1,033.03**	**43.0%**
8.3.1.4	Repair	1.1	1.3	$0.00			
8.3.1.5	Testing, rod assembly & burn-in	0	0	$6,552.00			
8.3.1.5.1	Full electronic test	1.1	1.3	$0.00			
8.3.1.5.2	rod assembly	1.1	1.3	$6,552.00	**$9,369.36**	**$2,817.36**	**43.0%**
8.3.1.5.3	burn-in	1.1	1.3	$0.00			
8.3.1.6	Documentation	0	0	$0.00			
8.3.1.6.1	Assembly, Test, Ship/receive	1.1	1.3	$0.00			
8.3.2	Assembly of 600 modules: ramp-up	0	0	$119,467.20			
8.3.2.1	Mechanical Assembly	1.1	1.3	$57,528.00	**$82,265.04**	**$24,737.04**	**43.0%**
8.3.2.2	Wirebonding	1.1	1.3	$26,208.00	**$37,477.44**	**$11,269.44**	**43.0%**

8.3.2.3	Inspection	1.1	1.3	$5,241.60	**$7,495.49**	**$2,253.89**	**43.0%**
8.3.2.4	Repair	1.1	1.3	$5,241.60	**$7,495.49**	**$2,253.89**	**43.0%**
8.3.2.5	Testing	0	0	$13,104.00			
8.3.2.5.1	Full electronic test	1.1	1.3	$0.00			
8.3.2.5.2	rod assembly	1.1	1.3	$13,104.00	**$18,738.72**	**$5,634.72**	**43.0%**
8.3.2.5.3	burn-in	1.1	1.3	$0.00			
8.3.2.6	Documentation	0	0	$12,144.00			
8.3.2.6.1	Assembly, Test, Ship/receive	1.1	1.3	$12,144.00	**$17,365.92**	**$5,221.92**	**43.0%**
8.3.3	Assembly of 6000 modules	0	0	$912,740.00			
8.3.3.1	Mechanical Assembly	1.1	1.3	$239,700.00	**$342,771.00**	**$103,071.00**	**43.0%**
8.3.3.2	Wirebonding	1.1	1.3	$273,000.00	**$390,390.00**	**$117,390.00**	**43.0%**
8.3.3.3	Inspection	1.1	1.3	$21,840.00	**$31,231.20**	**$9,391.20**	**43.0%**
8.3.3.4	Repair	1.1	1.3	$54,600.00	**$78,078.00**	**$23,478.00**	**43.0%**
8.3.3.5	Testing	0	0	$273,000.00			
8.3.3.5.1	Full electronic test	1.1	1.3	$109,200.00	**$156,156.00**	**$46,956.00**	**43.0%**
8.3.3.5.2	rod assembly	1.1	1.3	$54,600.00	**$78,078.00**	**$23,478.00**	**43.0%**
8.3.3.5.3	burn-in	1.1	1.3	$109,200.00	**$156,156.00**	**$46,956.00**	**43.0%**
8.3.3.6	Documentation	0	0	$50,600.00			
8.3.3.6.1	Assembly, Test, Ship/receive	1.1	1.3	$50,600.00	**$72,358.00**	**$21,758.00**	**43.0%**
8.4	Support Structures	0	0	$126,112.00			
8.4.1	Equipment	0	0	$0.00			
8.4.1.1	Support Cylinder Gluing Jigs	0	0	$0.00			
8.4.1.1.1	Ribbon and Cooling Tube Jig	0	0	$0.00			
8.4.1.1.2	Precision ledge placement jig	0	0	$0.00			
8.4.2	Assembly	0	0	$126,112.00			
8.4.2.1	Attachment of cooling tubes and ribbons	1.2	1.3	$47,908.00	**$74,736.48**	**$26,828.48**	**56.0%**
8.4.2.2	Attachment of precision positioning ledges	1.2	1.3	$78,204.00	**$121,998.24**	**$43,794.24**	**56.0%**
8.5	Transportation	0	0	$102,000.00			
8.5.1	Shipments to CERN	1	3	$102,000.00	**$306,000.00**	**$204,000.00**	**200.0%**