A Fermilab-Based CMS Silicon Tracker Group

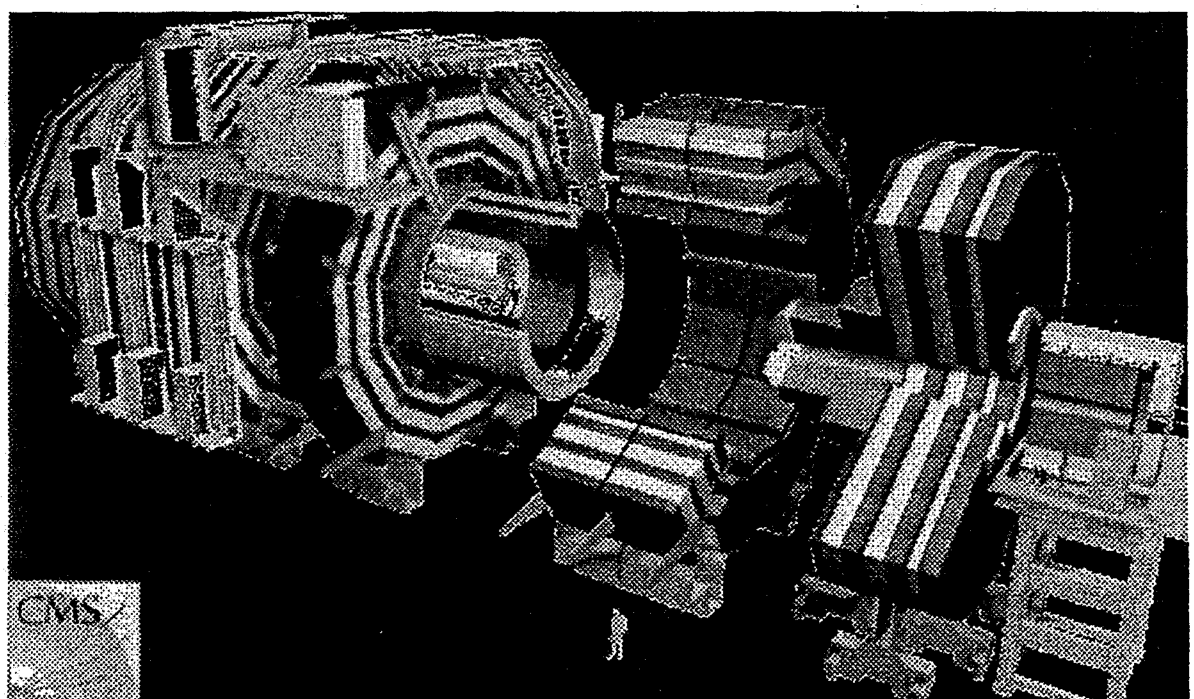
B. Flaugher, U. Heintz, J. Incandela, R. Lipton, P. Lukens,
S. Mishra, P. Rapidis, L. Spiegel, D. Stuart, S. Tkaczyk
Fermi National Accelerator Laboratory, Batavia Illinois, 60510

D. Buchholz
Northwestern University, Evanston Illinois 60208

S. Blusk, M. Kruse, P. Tipton
Rochester University, Rochester New York, 14627

D. Benjamin
Texas Tech University, Lubbock Texas, 79409

Version 2.01 8 June, 1998



Introduction

This note is a proposal by a number of U.S. scientists to participate in the Compact Muon Solenoid[1] (CMS) experiment now in preparation for the Large Hadron Collider (LHC) at CERN. The group includes physicists now engaged in the Fermilab experimental program including many who are involved in the construction of silicon detectors for the CDF and DZero Collider experiments. Our group has considerable experience with silicon microstrip detector design, fabrication, and operation, which can be employed to the benefit of the CMS silicon project. Similarly, the Fermilab Silicon Detector Center (SiDet) is an extensive state-of-art detector design and fabrication facility, which could be used to assist in the fabrication of the CMS silicon tracker.

The Fermilab Collider schedule for Run II calls for completion of the silicon detectors for CDF and DZero by early 2000. Sometime before their completion, fabrication capacity at SiDet will begin to be idle and could be used for other endeavors. This period is well matched to the scheduled start of fabrication of the CMS silicon tracker and represents an exceptional opportunity for both the CMS and Fermilab communities. It affords the latter with an opportunity to participate in the LHC physics program without disrupting their run II obligations while providing the former with significant silicon detector expertise and production capability.

The idea for a Fermilab-based participation in the CMS silicon tracker gained impetus during discussions that members of the CDF Intermediate Silicon Layer (ISL) detector had with their Pisa collaborators. These discussions, which entailed a fruitful exchange of ideas between the CDF and CMS silicon projects, also led to the organization of a workshop held at Fermilab on November 24-25, 1997 where the possibility of a Fermilab-based participation in the CMS silicon project was explored. The workshop generated significant interest among the Fermilab community and a group was formed to further pursue this possibility. A presentation was then made at CERN on March 10, 1998 in which it was proposed that the group become a member of the CMS Silicon Tracker collaboration. The proposal was accepted by CMS along with a promise to provide materials and partial financial support. At that time the exact role of the group was not determined but was envisioned to likely be that of constructing a significant portion of the silicon tracker modules and a portion of the larger final structures.

In this note, after brief descriptions of the CMS silicon tracker, the Fermilab Silicon Detector Center, and our group, we propose specific ways in which we could contribute to the CMS silicon tracker project.

[1] *The CMS physics program is described in: http://cmsinfo.cern.ch/cmsinfo/LoI/LOI.html*
Technical information about the detector can be found at : http://cmsinfo.cern.ch/cmsinfo/TP/TP.html

Overview of the CMS Silicon Tracker

The CMS silicon tracker design was recently modified. The present layout (referred to as V4), was adopted on December 9, 1997.[2] It is comprised of a Central Barrel and Forward Disk assemblies as shown in Figures 1 and 2. The barrel has 5 layers and triplets of smaller disks (mini-endplugs) at each end. Each barrel layer has detector modules supported by cylindrical carbon fiber shells. The shells are split longitudinally into half-shells as shown in Figures 3 and 4. The longest shell is 1.7 m. Table I contains the parameters for the Barrel which is composed of 3,168 silicon microstrip modules of five different types with a total of ~3 million channels. An individual barrel module is shown in Figure 5. The mini-endplug disk layout is shown in Figure 6.

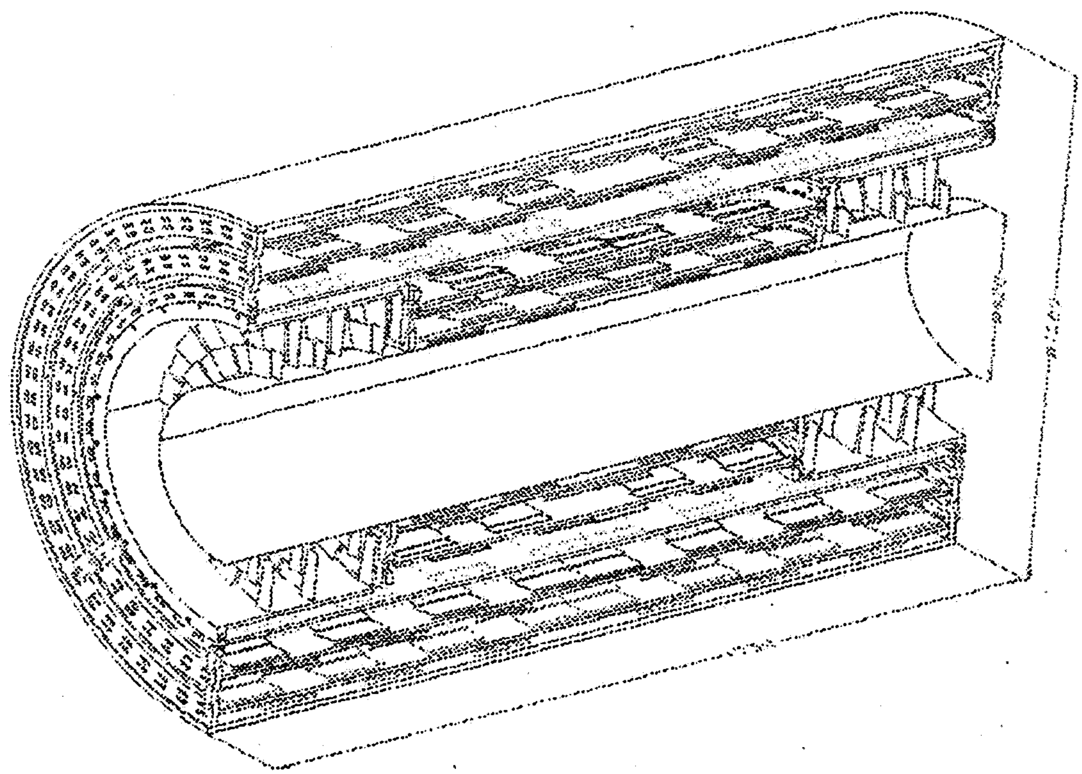
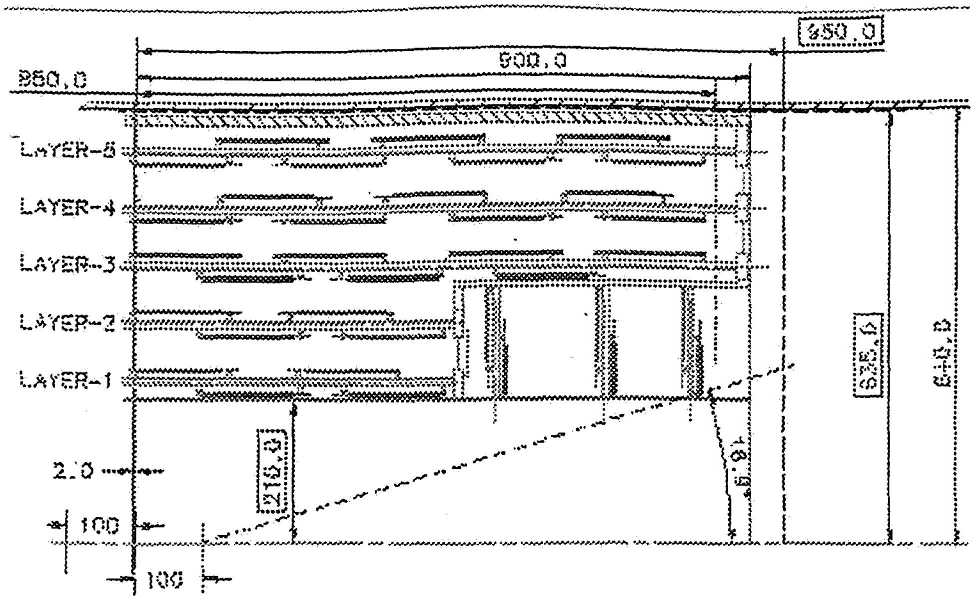


Figure 1. One half of the central barrel in the r-z plane showing the positions of barrel layers and mini endplug disks.

[2] *Technical Design Report now in preparation.* See *http://cmsdoc.cern.ch/~klaus.*



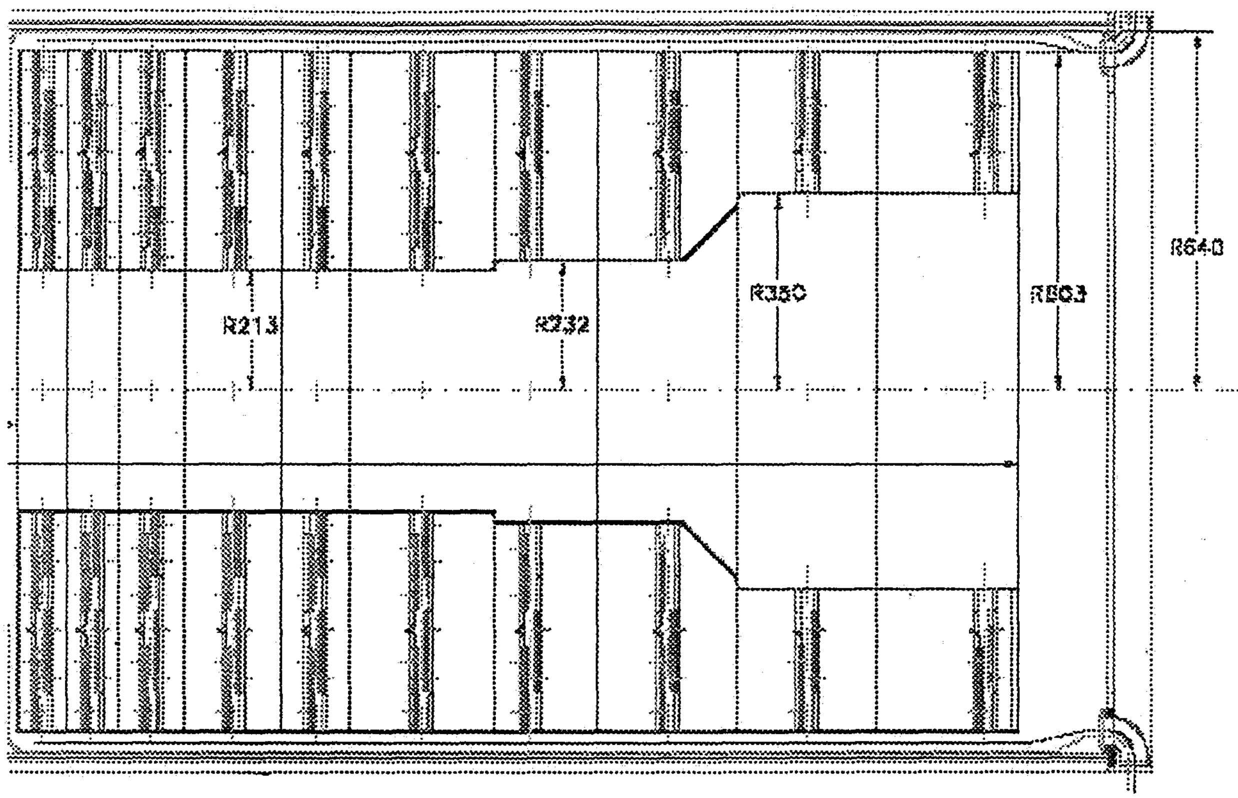


Figure 2. Layouts of one quadrant of the barrel system (top) and one half of the forward disk system (bottom).

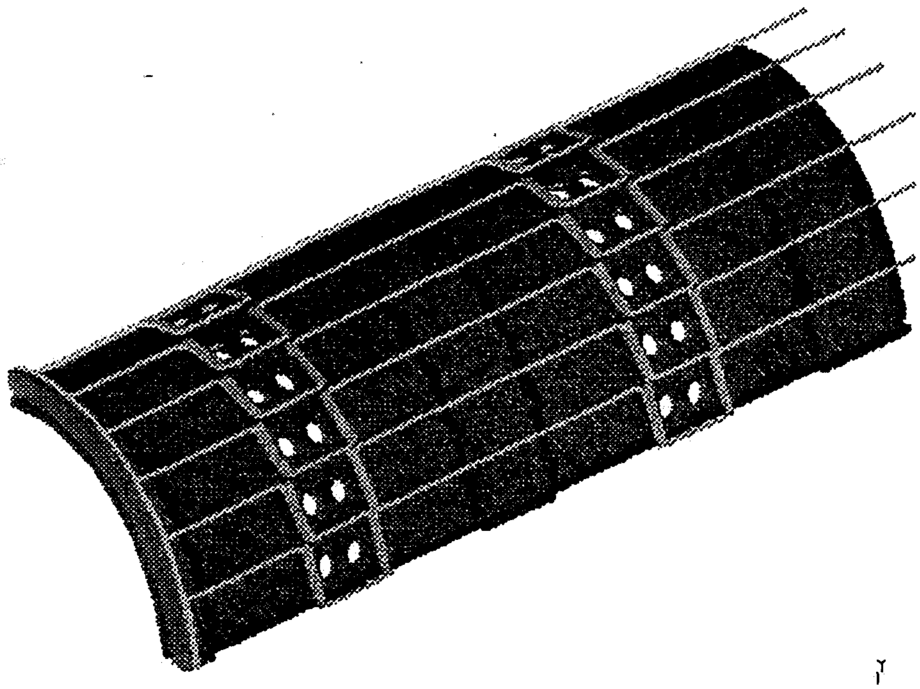


Figure 3. View of a portion of a central barrel half-cylinder support structure prior to installation of detector modules. The structure is a sandwich of 2 carbon fiber cylinders separated by carbon fiber omega beams held in place by circular hoops. Cooling lines (light blue) are shown along with high thermal conductivity ledges (yellow) which contact the electronics hybrids. Carbon fiber ribbons (red) are used to support the detector modules and ledges.

Table I: Barrel Silicon

Layer Number	Radius [mm]	Module Type*	Modules in ϕ	Modules in z	Total modules	Total chips	Cumulative modules	Cumulative chips
1-A	217	A	26	4	104	1248	104	1248
1-B	249	A	26	4	104	1248	208	2496
2-A	304.5	A'	36	4	144	1440	352	3936
2-B	336.5	A'	36	4	144	1440	496	5376
3-A	391.5	B	44	8	352	2112	848	7488
3-B	423.5	B	44	6	264	1584	1112	9072
4-A	479	B'	54	8	432	1728	1544	10800
4-B	511	B'	54	6	324	1296	1868	12096
5-A	566	C	62	8	496	2976	2364	15072
5-B	598	C	62	6	372	2232	2736	17304
Disk Inner	218	D	36	6	216	2160	2952	19464
Disk Outer	354	E	36	6	216	2160	3168	21624

* Modules A(A') : double-sided 61 (81) μm pitch in ϕ with 8 (6) readout chips with 128 channels per chip and 122 μm pitch in z with 4 readout chips. 100 mrad stereo angle.

Module B (B') : single-sided 81(122) μm pitch in ϕ 6(4) readout chips.

Module C: double-sided 122 μm pitch in ϕ (4 readout chips) and 244 μm pitch in z (2 readout chips) with a 100 mrad stereo angle.

Modules D(E) : double-sided 60 (74) μm pitch in ϕ with 6 readout chips and 89 (111) μm pitch in z with 2 readout chips.

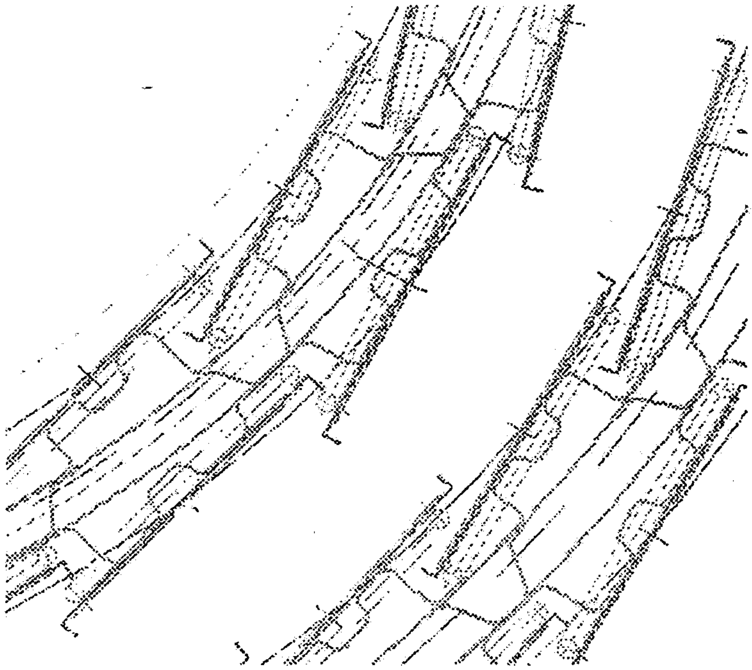


Figure 4. Cross-sectional view of the barrel cylinders showing the carbon fiber cylinders separated by carbon fiber Ω shaped channels in the axial direction of the cylinder. Also shown are the carbon fiber ribbons supporting the detector modules.

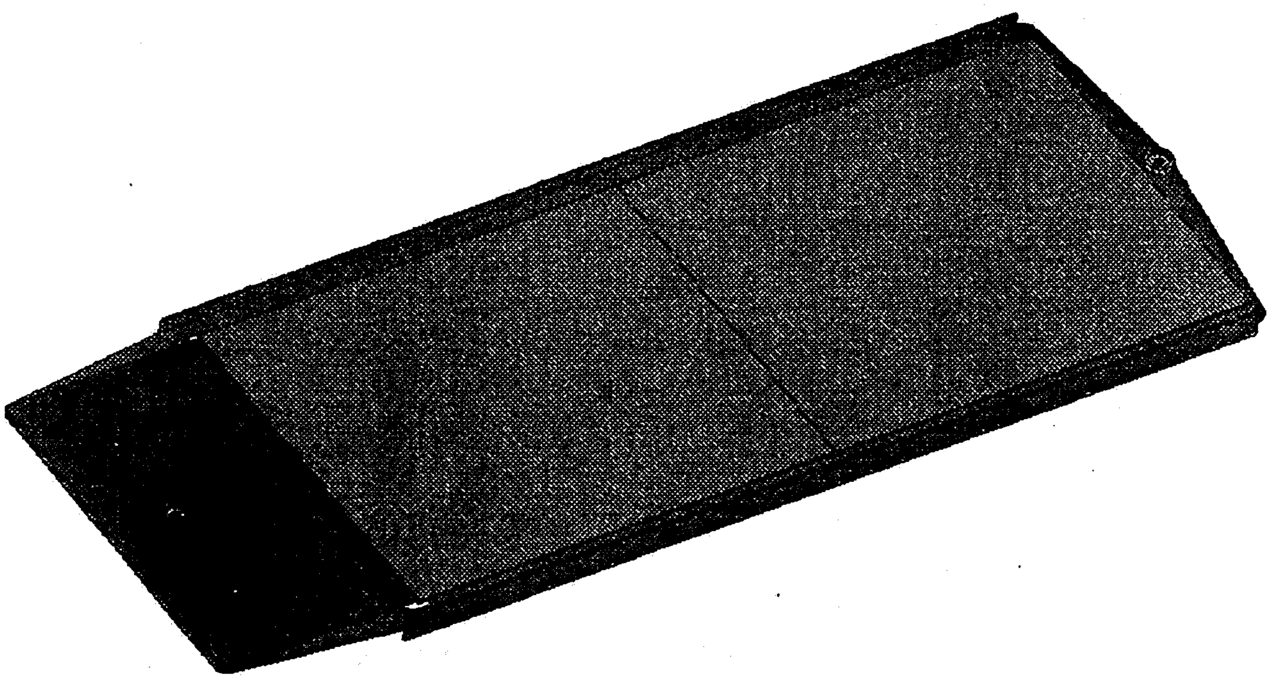


Figure 5. Single-sided CMS module. The module consists of a C fiber substrate (black), 2 microstrip sensors (blue) and an electronic readout hybrid (red). The hybrid is not mounted on the silicon.

The forward disk systems (Figure 2 and Table II) contain 10 disks at each end. These cover the region 22 < r < 59 cm and are composed of 4 concentric rings. Disks 1 through 6 are each composed of all 4 ring types (see Table II), while disks 7 and 8 use the outer 3 rings, and disks 9 and 10 use only the outer 2 rings. Rings 1 and 4 are double-sided. The strip pitches on rings 1 through 4 are 62, 83, 124 and 248 μm, respectively. The disk systems contain a total of 2800 modules with approximately 1.8 million channels.

Table II: Forward Disks

Disk type	Rings in disk	Rmin – Rmax (mm)	No of modules	Double or Single sided	Chips per module	Chips in Ring
A	1	220-300	36	DS	6+6	432
	2	290-400	36	SS	4	144
	3	390-490	48	SS	4	192
	4	480-590	60	DS	4+2	360
	Total	220-590	180			1128
B	2	290-400	36	SS	4	144
	3	390-490	48	SS	4	192
	4	480-590	60	DS	4+2	360
	Total	290-590	144			696
C	3	390-490	48	SS	4	192
	4	480-590	60	DS	4+2	360
	Total	390-590	108			552

Disk Number («Wheel»)	Number of Disks	Type of disk	Modules per disk	Chips per disk	Number of modules in these disks	Number of chips in these disks
±1,±2,±3,±4,±5,±6	12	A	180	1128	2160	13536
±7,±8	4	B	144	696	576	2784
±9,±10	4	C	108	552	432	1728
Total all wheels					3168	18048

In summary, the CMS tracker is comprised of a total of ~6,000 modules containing ~5 million separate readout channels. This is roughly 4 times the number of modules and 3 times the channel count of the combined CDF and DZero run II silicon detectors.

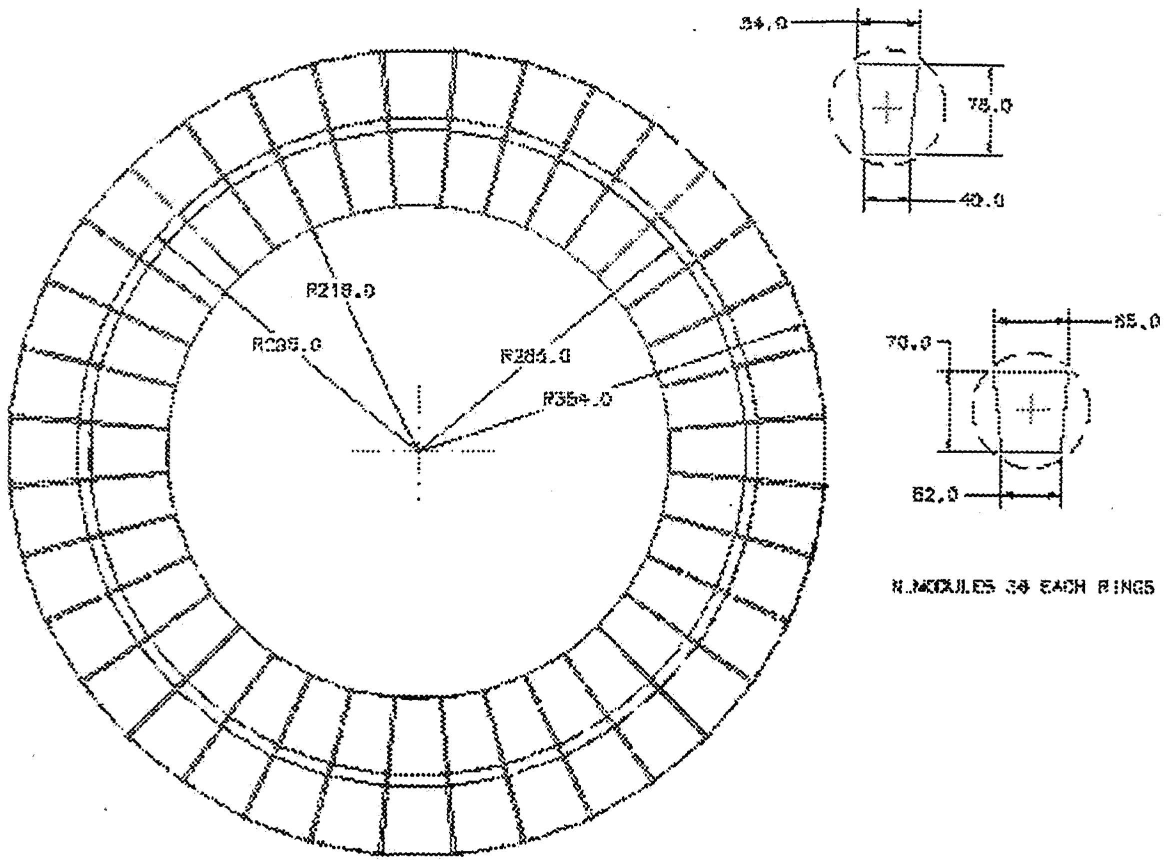


Figure 6. Layout of the mini-endplug disks to be installed in the barrel region as seen in Figures 1 and 2.

The Fermilab Silicon Detector Center (SiDet)

The Fermilab Silicon Detector Center was built primarily to house the construction of the run II CDF and DZero silicon detectors and to support other precision detector projects and R&D. The CDF run II silicon detector consists of approximately 656 double-sided modules ("half-ladders") of 6 main types having total silicon surface area of 5.97 m^2 and a total of 708,608 channels. The DZero detector will contain 768 modules of 14 types with 792,576 channels and a silicon area of ~3.0 m^2. The two systems combine to 1424 modules and ~1.5M channels. While this is only a small fraction of the size of the CMS system described above, it should be noted that the majority of the modules are considerably more complicated and difficult to build than those planned for CMS. This is due to the fact that most run II modules will have electronics placed directly on top of the silicon and be installed at small radii relative to the beam where they will be used for precise track impact parameter measurement. The latter requires more strict mechanical tolerances and more complicated barrel assemblies. Only the CDF ISL modules and the DZero disk modules are similar in philosophy and design to the CMS barrel and disk modules.

It is anticipated that the fabrication period for most of the run II modules will be one year. As a result, SiDet has prepared for large volume production. SiDet will have a peak staff of roughly 25 technicians. The center has also purchased a large suite of precision equipment, and has constructed several large clean and semi-clean spaces.

Table III catalogs the various equipment now installed or soon to be installed. Table IV lists the clean and semi-clean spaces. The main building instrument used in silicon detector manufacture is the Coordinate Measuring Machine (CMM). SiDet currently has 13 CMM's of varying size and precision. The smallest (Zeiss UMM 500's and several of the Giddings & Lewis machines), have precision ranging from ±1.5 to ±5.0 μm and will be used for module construction. The largest machines such as the LK and the Brown & Sharpe will be used for final assembly of modules into completed vertex and tracking chambers. These have precision on the order of ±10 to ±15 μm.

In addition to the CMM's used for module and barrel assembly, SiDet has an OGP optical measuring system (OMS) which is used for fast automatic inspection and characterization of modules to verify that construction tolerances are met. A smaller Metronics OMS may be used for inspection or small module assembly. SiDet has 3 fully automatic Kulicke &Soffa (K&S) 1478 wirebonders and one manual wirebonder. It is expected that at least one additional wirebonder will be purchased in order to have adequate capacity for the ~3.5 million wirebonds required by the run II silicon detectors. Three stereo video microscopes will be purchased soon for wirebond inspection and repair.

Other miscellaneous equipment at SiDet include 4 infra-red laser test stands with precision x-y positioning tables that can be integrated with data acquisition systems to enable strip-by-strip illumination and response measurement. There are also a number of detector probe stations available with two more to be installed this year. Finally, there are a number if micro-manipulators used for precise dye attachment, and numerous auxiliary electronic and mechanical devices.

Table III : SiDet Equipment

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
LK G80C	CNC	1.0	2.0	0.8	.013/450
DCC machine for ISL (1998)	CNC	1.0	1.0	1.0	.014/650
Zeiss UMC850	CNC	0.85	1.2	0.8	.010/400
Zeiss UPMC850	CNC	0.85	0.7	0.6	.008/400
4 Zeiss UMM500 (1-2 more 1998-99)	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
3 Kulicke & Soffa 1478 Automatic Wirebonders - 1 Hz auto. Bond rate
1 Kulicke & Soffa 8090 Automatic Wirebonder - 5 Hz auto. Bond rate - (1999)
1 Hughes 2470-V Automatic Deep access wirebonder (1998)
1 Kulicke & Soffa Manual (deep access) Wirebonder
2 Probe stations (1-2 more automatic probe stations in 1998)
4 Laser test stands with xy-tables
3 stereo video Microscope with xy-tables for inspection and repairs (1998)
Various Micro-manipulators and other ancillary electronics and measurement systems

Notes:

Volumetric accuracy is determined by measuring the length of a ball bar in 20 different locations along the edges and diagonals of the work zone. Although the ball bar is an uncalibrated length, the same (fixed but unknown) length is measured in each of the positions. The range of all the ball bar lengths is designated as the volumetric accuracy. The table lists both the range and ball bar length in millimeters.

The planar accuracy for an optical measurement system is determined in a similar fashion using a glass scale standard. It is defined as the range of all the distance measurements.

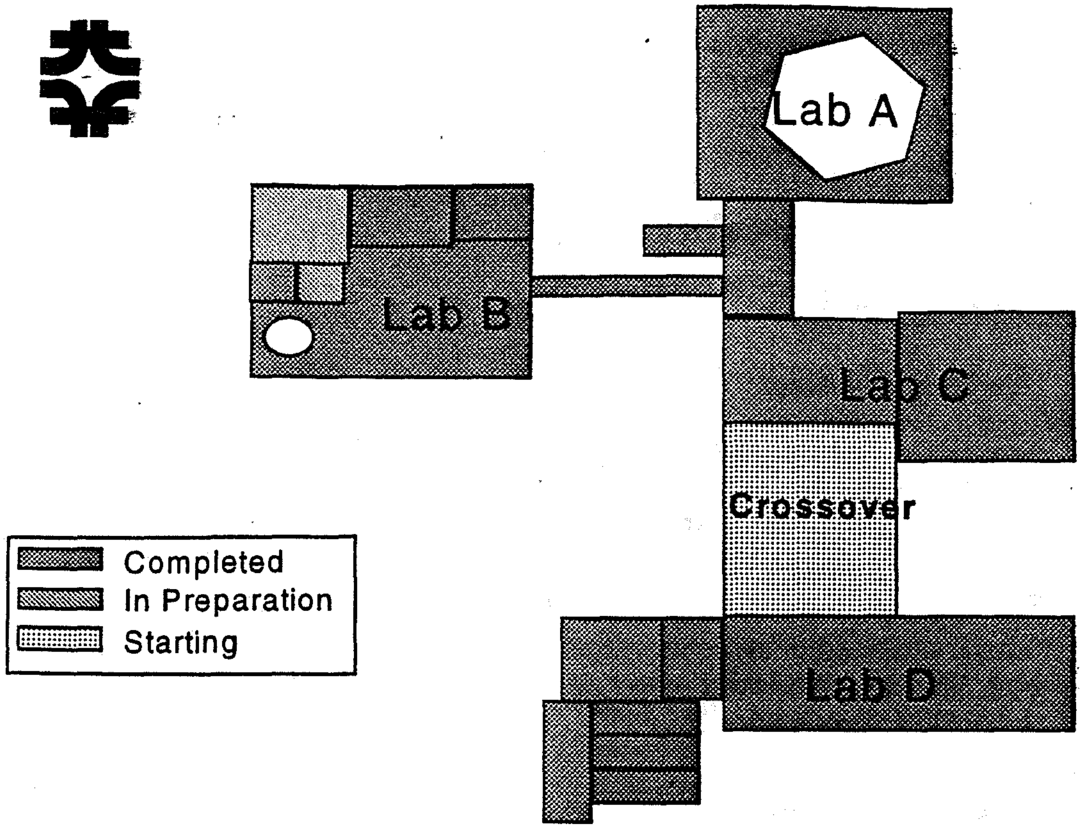


Figure 7. Layout of the Silicon Detector Center at Fermilab. Module production including wirebonding and testing takes place in Lab D. Lab C is reserved for final assembly of barrels and other large structures. Lab A is mostly dedicated to R&D but will be used for disk production as well. Lab B is a general work area used for machining, fixture assembly and engineering studies. The crossover will be primarily used office space and additional clean space.

Table IV : 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 is housed in the converted buildings of the old Neutrino Line Laboratories at FNAL. A layout of the center is shown in Figure 7. Roughly 1100 m^2 of high quality clean or semi-clean space will be contained in the center along with another ~500 m^2 of general working space. The latter includes a small machine shop. There are plans to install some equipment to give SiDet the ability to mold carbon fiber in future.

SiDet Capacity

The Silicon Detector Center plans to build on the order of 40 modules per week for run II detectors in Lab D and Lab A. Wirebonding and electronic testing capacity will be adequate to maintain this pace. Figures 8-10 show a portion of the Lab D module construction resources available. Lab C will be used to assemble 3 CDF SVXII barrels, 2 ISL barrels and 6 D0 Barrels. Labs A and C will be used for assembly of D0 disks. All final assemblies will occur in Lab C. The Lab C clean room is in fact adequate to allow nearly all of the larger structures mentioned here to be constructed in parallel. Figure 11 shows the Browne & Sharpe 3m CMM in Lab C where it will be used for the final assembly of the full CDF silicon system.

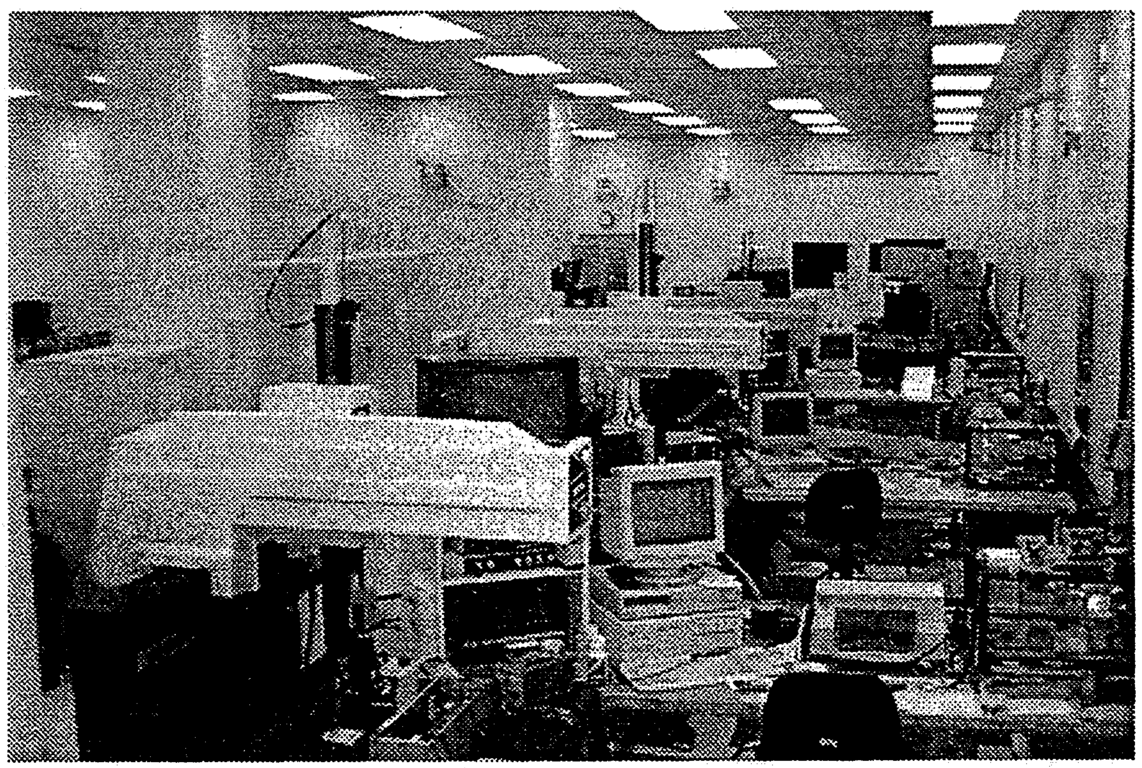


Figure 8. A part of the SiDet module assembly area in Lab D containing G&L CMM's to be used by CDF.

Figure 9. The Lab D Wirebond area. Three automatic K&S 1478 wirebonders are shown as well as a manual bonder (where technicians are seated).

Figure 10. The area of Lab D containing Zeiss UMM 500's and a Zeiss UPMC 850 to be used for DZero Run II module construction.

For more simple structures such as the CMS single-sided module shown in Figure 5, we estimate that at maximum capacity, SiDet could produce as many as ~90 per week. CMS double sided modules (made up of single-sided silicon sensors glued to the front and back of a carbon fiber substrate) could be produced at somewhat less than half the single sided module rate.

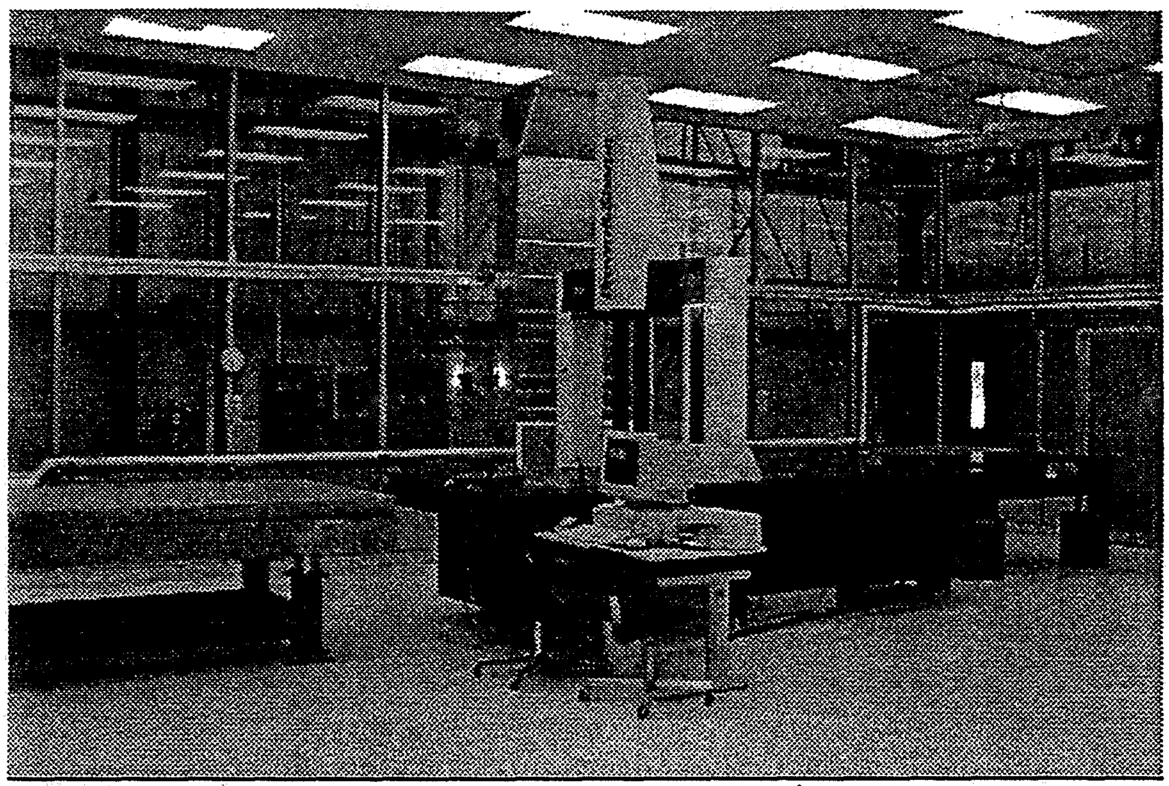


Figure 11. The Brown and Sharpe 3 m CMM in the Lab C clean room.

Group Expertise

The members of the Fermilab community who author this proposal offer substantial expertise which has been accumulated in the successful construction and long-term operation of two silicon vertex detectors in hadron collider environments, and the extensive design, development, construction, and testing of components for the more complicated Run II systems. We have capabilities in a broad range of areas related to silicon detectors including : design, electronics, probing, mechanics, cooling, interlocks, and fabrication. In addition we have experience in the alignment of silicon detectors, the optimal use of data, pattern recognition (from clustering to tracking), and physics analyses based on silicon vertexing such as b tagging in top decays (Figure 12) and a large number of B physics measurements in hadron collisions. This experience will deepen in run II of the Fermilab collider.

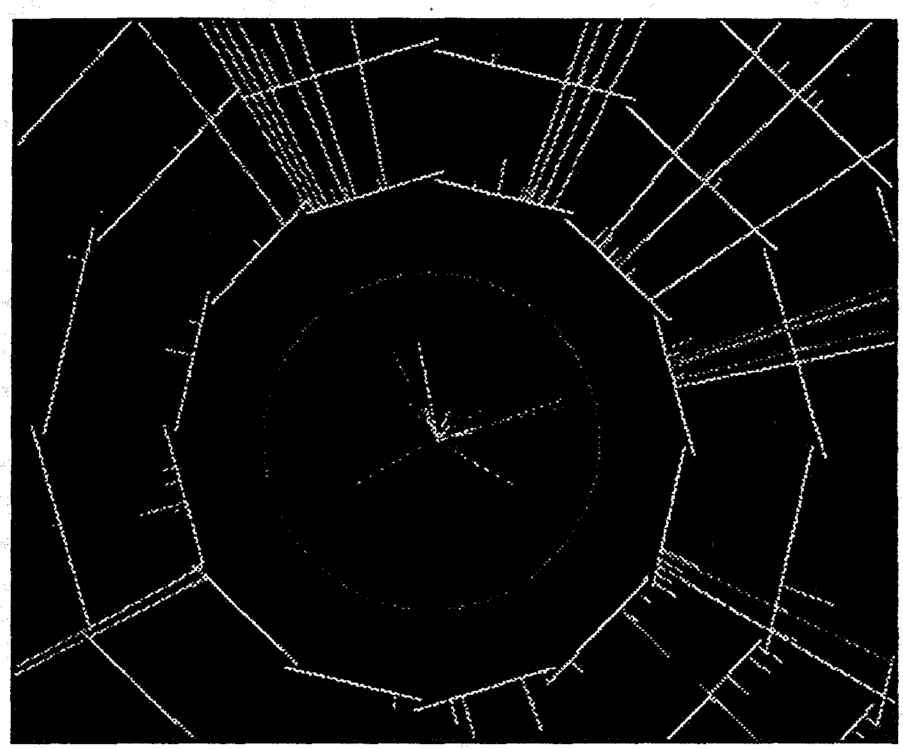


Figure 12. The first CDF b-tagged top event, (September 1992), as seen in the inner layers of the SVX detector. Green lines represent tracks from the primary vertex while red lines are for tracks from significantly displaced vertices. In the b jet at roughly 2 o'clock, the track density is very high. Roughly 20% of all tracks in b jets from top decay overlap at least one other track at the innermost layer of the silicon detector due. Such high track densities have not yet been experienced elsewhere but should be regularly encountered at the LHC.

Proposed Contributions

Our group can make a number of substantial contributions to CMS. Initially, the group can bring its experience to bear in reviewing the CMS silicon system and sub-system designs. In the construction phase, we could construct modules and larger support structures. During final assembly and testing we would plan to make a substantial contribution. Finally, we would be involved in the commissioning and operation of the detector as well as the analysis and understanding of data and development of pattern recognition with the ultimate goal of contributing to the CMS physics program.

In formulating our proposed contribution to the CMS Silicon tracker, we have sought to be of maximum assistance to CMS, while at the same time minimizing the costs incurred by either CMS or Fermilab. In this section we present an example of how this can be achieved. We describe a proposal in which we would build several large precision assembly fixtures to be used by CMS. As seen in more detail below, our infrastructure and experience enable us to do this at very low cost. CMS would then agree to pass on the savings that result from this exercise to FNAL where it would be used to fund the technical manpower needed to build one full layer of the CMS silicon tracker barrel.

CMS would provide all of the basic materials required for one layer's module and cylinder construction. Fermilab, in collaboration with INFN Pisa, could design and build the large, precision cylinder assembly fixtures. We have acquired a significant amount of experience successfully building such fixtures in the past. Furthermore, a key element of these fixtures is a high precision, heavy load, rotary table such as the Zeiss RT05 of which there are currently 5 at SiDet. These were obtained along with a number of CMM's internally transferred to FNAL from another DOE facility. Such rotary tables are hard to obtain. Used models sell for as much as 40k$ while new ones are of order 80k$. In discussions with Pisa engineers, we have concluded that we could save CMS a very considerable amount of money by providing such fixtures along with loans of the rotary tables to the main tracker construction sites. We estimate the total cost to complete a fixture would be 30k$ for FNAL whereas it would cost of order 100 k$ to CMS. FNAL could construct 2 such devices, (one for Pisa and one for CERN, either of which could be used at FNAL before shipping overseas).

Fermilab has agreed to underwrite the cost of SiDet infrastructure, maintenance and support personnel. The residual costs are small and are dominated by technician's salaries. It is possible that some amount of this labor could be obtained without cost to CMS. In particular, Fermilab technicians who are not fully occupied by other projects could assist the CMS effort for short periods of time. Funds would be needed to pay for the technicians who are fully dedicated to CMS work and required to maintain a consistent production pace.

To facilitate the financial support of the construction tasks performed at FNAL, CMS could purchase the large rotary table assembly fixtures discussed above from FNAL at full, or nearly full, value. Fermilab could agree to use this money to pay for much of the CMS layer construction. In this way, *one* full layer of the barrel silicon tracker could be constructed at FNAL at minimal cost. Moreover, in establishing the ability to construct such a structure at Fermilab, and in view of the extensive capacity available at SiDet, CMS would be in a position to transfer responsibility for the construction of other layers to FNAL in the event that this became necessary for whatever reason. Of course, in these cases, CMS would need to fund such efforts. Depending upon schedule considerations and in view of lower labor costs in the USA, this could be an attractive option for CMS.

To be specific, we would propose to build layer 4 of the barrel silicon strip detector. This is the largest layer we could build with machines currently installed at SiDet. Layer 4 is made up of 756 single sided modules with 4 readout chips on each. These modules are similar to the CDF SVX and SVX′ detectors in their simplicity and hence are considerably more simple to construct than some of the modules planned for the CDF and D0 run II detectors. We can therefore reliably estimate that a single team consisting of two full time mechanical technicians together with physicists working in shifts could maintain a construction pace of 10-15 CMS barrel modules per week. At this pace we would complete the layer 4 modules, including spares, in approximately 1.5 years. This process includes precision assembly, wirebonding, mechanical inspection, and electrical testing. Table V summarizes the equipment and labor that would be needed for such an endeavor.

All of the machines listed already exist at SiDet. Dry storage boxes and electronics test boxes could be adapted from run II D0 and CDF projects. Similarly, it may be possible to adapt module fabrication and wirebonding fixtures from those used for Fermilab run II projects at relatively low cost. Individual module handling boxes for storage would need to be manufactured but at low relative cost. Of course miscellaneous items, such as epoxy and other construction materials would be needed over the two-year construction period. We would estimate the cost of maintaining miscellaneous materials stores during production to be on the order of 25k$ per year.

Note that in addition to readout hybrids, sensors, and module substrates, we will require PREMUX data acquisition stands for quality assurance testing with laser and xy-table systems, and also for module burn-in. It is anticipated that sensors, substrates and hybrids would be provided by CMS. We estimate the cost of a PREMUX test stand to be of order $25k and may also be provided or paid for by CMS. Module construction would require two technicians for two years.

Table V : Module Production Equipment

	Layer 1	Layer 2	Layer 3	Layer 4
	Double-sided	Double-sided	single-sided	single-sided
Modules	208	288	616	756
Readout IC's	2496	2880	3696	3024
Sensors	832	1152	1232	1512
Probe stations	1	1	1	1
CMM's	1	1	2	2
Optical Inspection System	1	1	1	1
Wirebonders	1	1	1	1
Inspection stations	1	1	1	1
Chiller system	1	1	1	1
Dry storage boxes	1	1	3	3
Wirbonding jigs	0.25	0.25	0.5	0.5
Burn-in boxes	5	5	10	10
Add. FNAL resources in $US				
Module handling boxes	25	25	50	50
PREMUX DAQ Test stands	0.25	0.25	0.75	0.75
Module assembly jigs	1	1	2	2
Electronic test boxes	3	3	6	6
Technicians (man years)	2	2.5	2.5	2.5
Estimated cost in $US	$124,000	$144,000	$240,000	$240,000

For cylinder construction, the design and fabrication cost per assembly fixture is estimated to be 40k$. Assembly of two such fixtures and a complete Layer 4 cylinder would require an additional 1.5 to 2 technical man-years. This includes placement of the cables, cooling tubes, ribbons, cooling ledges, and installation of modules. Physicists will perform all testing of modules during construction. We estimate that the total M&S cost for construction of Layer 4 and 2 module assembly fixtures is $300,000. This does not include the sensors, hybrids, substrates, and cylinder components, which would be provided by CMS.

We are also considering participation in the online and offline code development, system tests, Monte Carlo simulation, test beam and radiation studies, pattern recognition, and of course Physics analysis. Many of these areas are complementary to ongoing work for Fermilab run II and run III and would be a natural extension of the work in which we are now involved.

Conclusion

In conclusion, we are a group of willing and capable physicists interested in making a substantial contribution to the CMS silicon tracker project. We plan to assist the CMS collaboration in the design, fabrication, final assembly, installation, commissioning, and operation of the CMS silicon tracker with a strong interest to later participate in the CMS physics program.

We have presented a proposal to build Layer 4 of the CMS silicon tracker along with two cylinder assembly fixtures. Our proposal has the virtue of minimizing new costs to either CMS or Fermilab while at the same time maximizing our contribution to the CMS tracker project.