Fermilab Test Beam Proposal for Diamond Tracking Detectors

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This proposal requests beam time at Fermilab during the 1999 Fixed-Target Run to test Chemical Vapor Deposition (CVD) diamond microstrip and pixel detectors. Our research in this area began nearly a decade ago when we realized that CVD diamond is a promising, radiation-hard alternative to silicon. Our work has been funded by DOE, TNRLC, and NSF; we are currently funded by an NSF MRI grant. Below we detail what we expect to accomplish in beam tests of diamond detectors as well as what resources are required.

Introduction to Diamond Detectors

In Table 1, we summarize the properties of diamond and, for comparison, those of silicon. The most distinctive feature of diamond is its large band gap, 5.5 eV. This large band gap along with the associated large cohesive energy are responsible for much of the radiation hardness of diamond. The large band gap also makes diamond an excellent electrical insulator. As a result, a large electric field can be applied without producing significant leakage current. Thus, there is no need for a reverse biased pn-junction and the diamond detector functions much like a "solid-state" ionization chamber. Diamond has two additional properties that are favorable compared to silicon. Its smaller dielectric constant yields a smaller detector capacitance and, thereby, better noise performance of the associated front-end electronics. In addition, even though diamond is an electrical insulator, it is an excellent thermal conductor with a thermal conductivity exceeding that of copper by a factor of five. A common problem with large strip detector systems is the management of the thermal load generated by the large number of electronic channels used in the detector readout. The handling of this thermal load would be simplified if the detectors are constructed from diamond.

Diamond appears ideal in many respects but it does have a limitation: the large band gap which produces many of its outstanding properties also means that its signal size is at most approximately half that of silicon for a given detector thickness in radiation lengths. This may be compensated by lower front-end electronic noise due to diamond's nearly non-existent leakage current and, for strip detectors, diamond's lower capacitive load.

In Fig. 1, we show the basic principle behind the use of diamond as a charged particle detector. Several hundred volts (~ 1 V/μm) is applied across a layer of diamond a few hundred microns thick. When a charged particle traverses the diamond, atoms in the crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. On average, 3,600 electron-hole pairs are created per 100 μm of diamond

Property	Diamond	Si
Band Gap [eV]	5.5	1.12
Breakdown field [V/cm]	10^7	3×10^5
Resistivity [Ω-cm]	$> 10^{11}$	2.3×10^5
Intrinsic Carrier Density [cm^{-3}]	$< 10^3$	1.5×10^{10}
Electron Mobility [$cm^2V^{-1}s^{-1}$]	1800	1350
Hole Mobility [$cm^2V^{-1}s^{-1}$]	1200	480
Saturation Velocity [km/s]	220	82
Mass Density [g cm^{-3}]	3.5	2.33
Atomic Charge	6	14
Dielectric Constant	5.7	11.9
Thermal Expansion Coefficient [K^{-1}]	0.8×10^{-6}	2.6×10^{-6}
Thermal Conductivity [W m^{-1} K^{-1}]	1000-2000	150
Cohesive Energy [eV/atom]	7.37	4.63
Energy to create e-h pair [eV]	13	3.6
Radiation Length [cm]	12.0	9.4
Spec. Ionization Loss [MeV/cm]	4.69	3.21
Ave. Signal Created/100 μm [e]	3600	8900
Ave. Signal Created/0.1% X_0 [e]	4500	8400

Table 1: The physical properties of diamond and silicon at 293K. [1]

traversed by a minimum ionizing track. These charges drift across the diamond in response to the applied electric field producing a signal that can be measured.

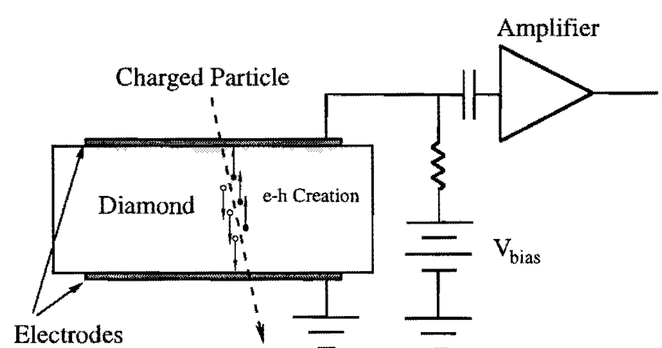

Figure 1: A schematic view of a diamond detector.

An interesting feature of diamond sensors is that they improve with exposure to radiation for exposures up to about 1 kRad. This "pump-up" effect is due to an increase of carrier lifetime caused by passivation of deep traps. Because diamond has such a large band gap there may exist traps more than 1 eV from the valence or conduction bands. Exposure to radiation fills these traps with electrons (holes) produced by the radiation. If the traps are far enough from the conduction (valence) bands, the rate of thermal ionization of these traps will be slow and they will remain passivated for long times. We have found that diamonds kept in the dark remained pumped for at least three months. Exposure to light of the energy of the traps rapidly ionizes the traps and depumps the diamond.

History

The collaborating institutions on this proposal bring with them an extensive and unique set of capabilities in diamond detector research. The groups from Rutgers and Ohio State pioneered the work on CVD diamond detectors in the DIAMAS proposal [4] to the SSC in 1989. Since 1994, these two groups have continued to play major roles in diamond detector research as founders and leaders of the RD42 collaboration [5] at CERN. From 1989 to 1993, the DIAMAS collaboration pioneered the field of CVD diamond detectors. This collaboration was the first to observe single minimum ionizing particles in CVD diamond [6]. In 1993, the first calorimeter-quality diamond wafers were produced and a diamond-tungsten calorimeter was constructed along with its readout electronics [7]. This device achieved the same energy resolution as a similar silicon-tungsten calorimeter demonstrating that diamond calorimetry works. This was also the first demonstration of large-scale production of CVD diamond detector material with 200 cm^2 of diamond produced in six months. Figure 2 show the enormous progress we have made in increased signal size over the past eight years.

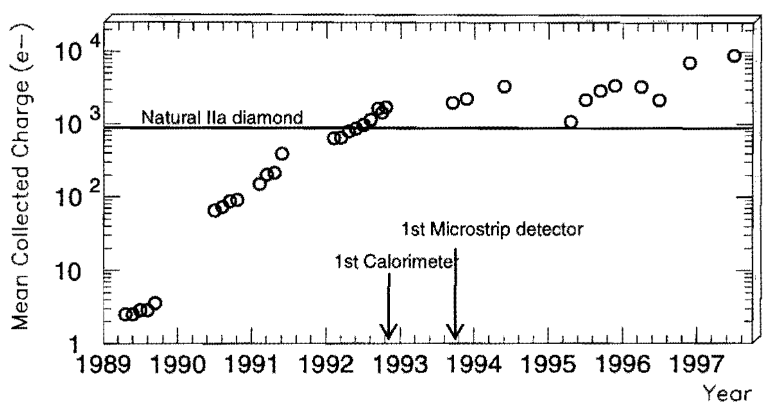

Figure 2: Pulse height of diamond detector for minimum ionizing track versus date.

Results of Prior Testbeams

Since 1994, the RD42 collaboration has worked on continuing to improve the quality of CVD diamond material, constructing and testing diamond microstrip and pixels detectors and testing the radiation hardness of diamond detectors. The first diamond microstrip detector was constructed and tested in 1994 [8]. Since then, diamond trackers constructed with 50 μm strip-pitch have yielded 12 μm spatial resolution, 98% efficiency and 50:1 peak signal-to-noise ratio with 1.5 μs shaping-time electronics [9, 10, 11]. In 1996, the first diamond pixel detector was constructed attaining a 22:1 peak signal-to-noise ratio. In this past year the first diamond tracker (50 μm pitch) was operated with 25 ns peaking-time electronics attaining a most probable signal-to-noise ratio of 7:1.

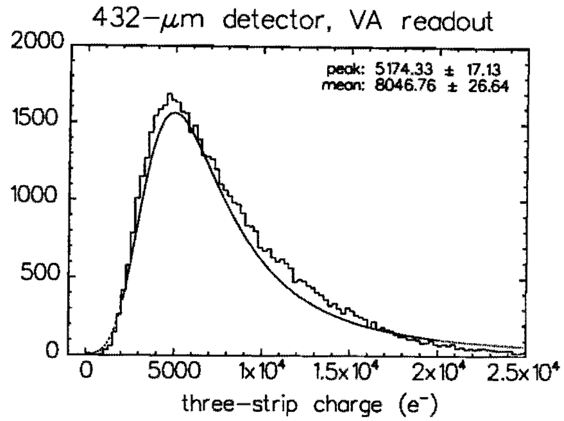

Figure 3: Pulse height distribution of 432-μm thick detector with VA-2 electronics.

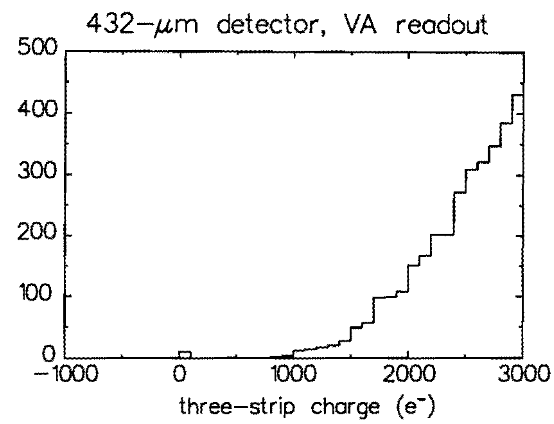

Figure 4: Detail of region near zero pulse height.

Figure 3 shows the pulse height distribution of a 432 μm thick diamond microstrip device readout with VA-2 electronics (1.5 μsec shaping time). The pulse height consists of the three-strip sum of the signal on the strip corresponding to the extrapolated hit plus the signal on each of the two neighboring strips. The mean collected charge for 100 GeV incident pions was 8,000 e^- while the most probable signal corresponded to a collected charge of 5,000 e^-. The ratio of the most probable signal size to single-channel noise was 40 to 1.

Figure 4 shows the distribution for signals less than 3,000 e^- indicating a clear separation of the distribution from zero. The spatial resolution achieved with this detector using a center-of-gravity position algorithm is shown in Figure 5. The residual distribution (measured hit position - extrapolated hit position) has a standard deviation of 15 μm, the digital resolution for 50 μm pitch.

CVD diamond is inherently polycrystalline in nature. As a result, the level of spatial uniformity of the average signal size is of interest since it could effect the spatial resolution achievable through charge sharing. With current statistics, the uniformity can be probed at the 100 μm $\times$ 100 μm level. Figure 6 shows the average signal size (grayscale coded) of a 2

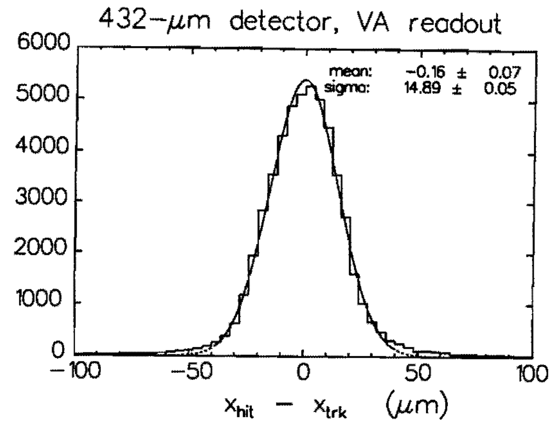

Figure 5: Position resolution of 432-μm thick detector using a center-of-gravity position algorithm.

mm $\times$ 2 mm area of diamond in 100 μm $\times$ 100 μm bins. On average, there are 40 tracks per bin. Comparing this same plot with Figure 7 in which the hit position is randomly scrambled indicates a nonuniformity in the diamond. A quantitative measure of this nonuniformity is given by the ratio of the standard deviation of the average pulse height per bin to the average pulse height. Finite statistics contributes about 8% to this value. When this is subtracted in quadrature the residual nonuniformity is about 30%. For comparison, the width of the Landau distribution is about 23% of its mean.

In the coming year, sufficient statistics needs to be accumulated to study the spatial uniformity at the 25 μm $\times$ 25 μm level. Similar effects can be seen when looking at the spatial dependence of position resolution. About the same level of statistics is needed to study resolution uniformity carefully and the same data set can be used as for the spatial uniformity study.

A program has begun to test diamond pixel devices bump-bonded to CMS and ATLAS pixel electronics. A successful test of a diamond device metallized with Ti/W electrodes in a 50 μm $\times$ 536 μm bricked pattern shown in Figure 8 has been performed. The size of the device is 4 mm $\times$ 8 mm and consists of 12 $\times$ 64 pixels. An ATLAS/3 readout chip was indium bump-bonded to this diamond by Boeing.

The device was tested in a 100 GeV/c pion beam at CERN. Figure 9 indicates the hit occupancy. There are several features to be noted. Two of the columns, 4 and 6, are "hot" due to a problem with the readout chip. These two columns were excluded from the analysis. The left half of the device has a higher hit density than the right half due to the beam not being centered. Figure 10 shows the distribution of the number of hits per pixel for the left side of the detector which saw the most beam. Out of these 256 pixels, only 6 had no hits indicating that 98% of the channels were successfully bonded.

Of the 49,000 tracks that were extrapolated to have passed through the active diamond area (excluding the regions under the two "hot" columns), there were 12,000 pixel hits that exceeded the 3,500 e^- threshold of the electronics. Figure 11 shows the pulse height distribution of these hits. Since the version of the ATLAS/3 electronics used was not radiation

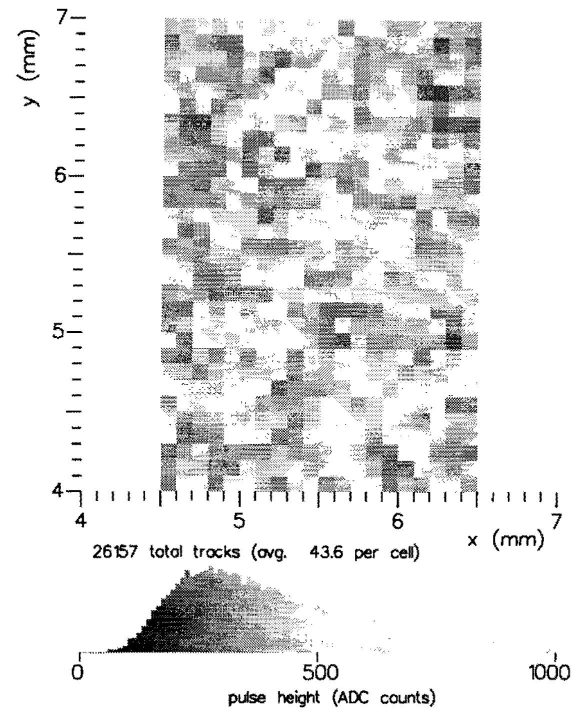

Figure 6: Mean collected signal charge vs. track hit position in 100 μm $\times$ 100 μm bins.

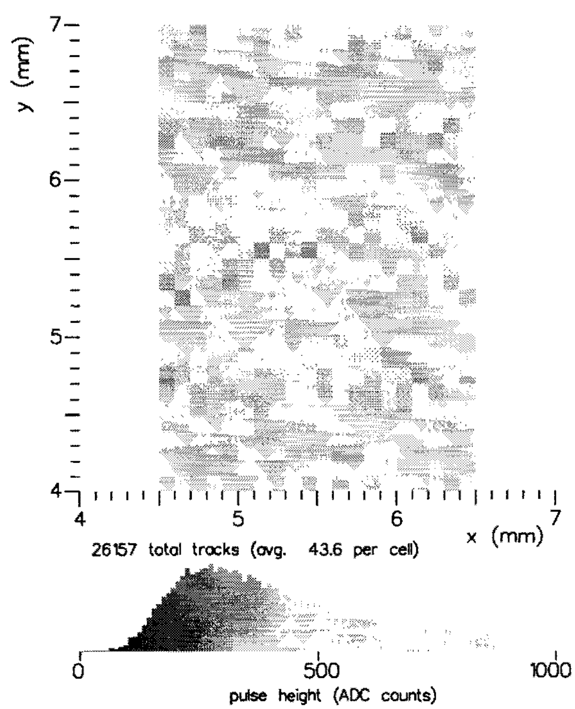

Figure 7: Same as Figure 6 but with the track position randomly scrambled.

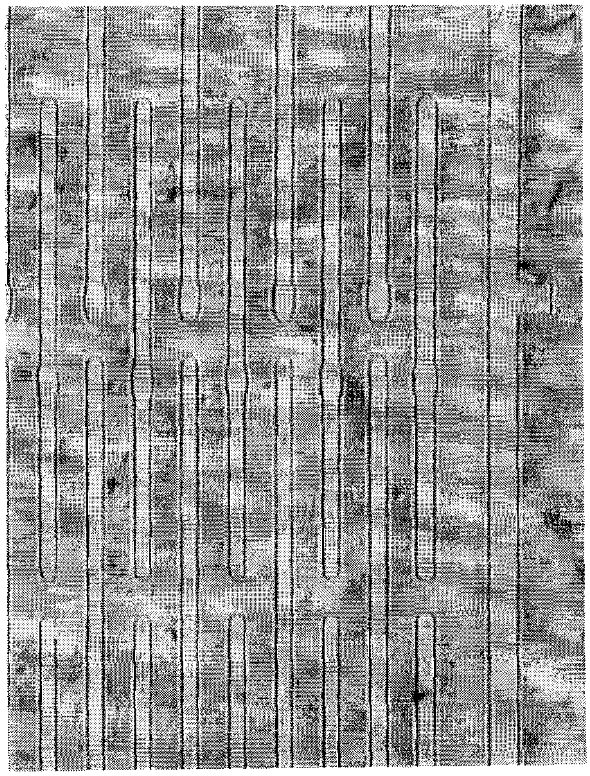

Figure 8: ATLAS/3 pixel pattern metallized on diamond.

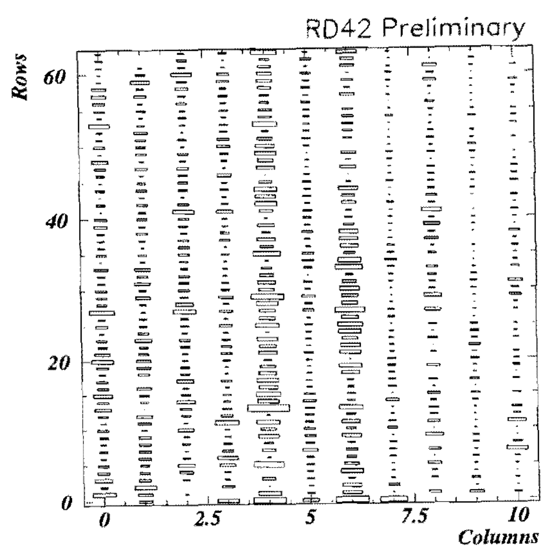

Figure 9: Number of hits per pixel.

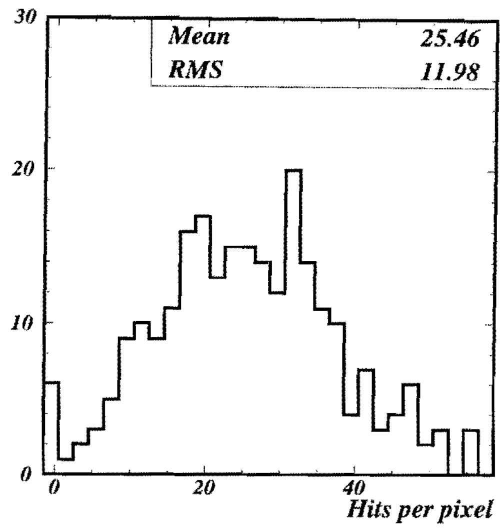

Figure 10: Distribution of number of hits per pixel.

hard, the diamond bonded to it was not able to be pumped up by exposing it to 1 kRad of ionizing radiation. Since this diamond had previously been configured as a microstrip tracker and had been tested in a beam, its single strip pulse height distribution when pumped was known. Overlaying this distribution onto the one measured for the pixel device, an efficiency of 50% would have been obtained if the diamond had been "pumped". Furthermore, the ATLAS electronics will eventually be operated with a threshold of 2,000 e^-. Based on the known charge distribution, the efficiency of the "pumped" diamond with a 2,000 e^- threshold would be 85%.

The position resolution of the the diamond pixel is shown in Figures 12 and 13. The resolution in the 50 μm direction is 14.8 μm and in the 530 μm direction it is 140 μm. Both are approximately the digital resolution.

Why Test Beams at FNAL Are Needed

It is clear from the above discussion that CVD diamond material is nearly of sufficient quality to meet criteria for use as vertex detectors in future collider experiments. Bench measurements using ^{90}Sr beta source are useful for coarse evaluation of newly produced material and for feedback to manufacturers. But a beam test environment is clearly the only way to get detailed information on the potential tracking performance of the material at hand in a relatively short amount of time.

The following list summarizes what needs to be measured for both strip and pixel detectors:

- spatial resolution
- hit efficiency

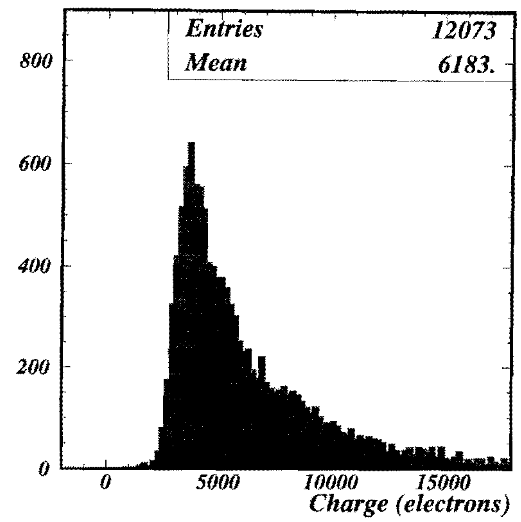

Figure 11: Collected charge in diamond pixel detector.

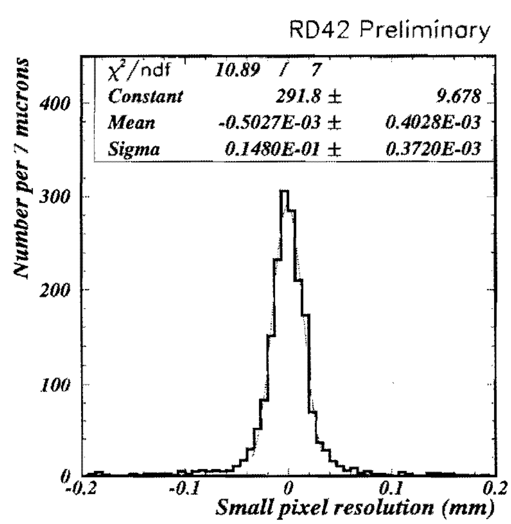

Figure 12: Pixel spatial resolution in 50 μm direction.

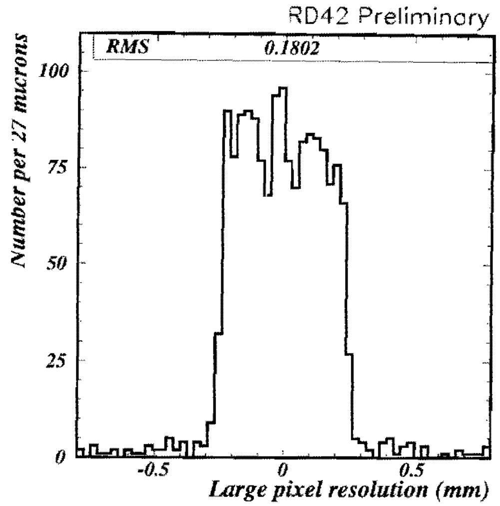

Figure 13: Pixel spatial resolution in 530 μm direction.

- comparison of pulse height distribution with that from ^{90}Sr measurements
- pulse height uniformity studies (high statistics needed)
- resolution uniformity studies (high statistics needed)
- Lorentz angle determination within a magnetic field

During the last few years there has been only one major supplier of detector grade CVD diamond. It takes several weeks to grow a wafer and comparable amounts of time to prepare the surface, deposit electrodes, examine test pieces from the wafer, and make final sample preparations for a test beam. Based on this growth-to-testbeam cycle time our experience has been that three to four test beam studies per year have been sufficient to keep up with the production of new diamond. However, during 1999 we expect to have material from two new manufacturers to test. We cannot expect any increased amount of testbeam time at CERN. We therefore need to look for alternative locations such as FNAL.

There are numerous advantages to incorporating a test beam at FNAL into our overall R&D program. Besides the obvious savings in travel time and expense, we have much closer connections to ongoing experiments at FNAL (CDF, KTeV, CMS, et al.) and hope to exploit these to share resources. Conversely, we are soon to lose two of our close (and hardworking) contacts at CERN due to graduation. Faster turnaround of data analysis can be expected from an FNAL testbeam because of existing high-speed networks in place between the Lab and our North American universities. This will provide more rapid feedback to the diamond manufacturers as well as to the overall R&D effort.

We plan to test specific prototype detectors, equivalent to those to be used in CMS and Atlas, CDF and perhaps BTeV.

Proposed Test Beam Program and Requirements

We have found that about five days of dedicated beam time is optimal to test five to ten devices. We are DAQ deadtime limited above 100 Hz into a 5 cm^2 area. High statistics are needed for some devices to determine position resolution and uniformity. Others need to be studied more quickly with, for example, frequent bias adjustments. During a given 5 day test beam, we plan to test at least three 1 cm^2 strip detectors, one larger strip detector 2 cm x 4 cm, and at least two pixel sensors bonded to pixel electronics.

We will supply the overall tracking telescope, readout electronics, and DAQ. Resources needed at FNAL are:

- charged particle beam with energy > 10 GeV to minimize effects due to multiple scattering
- flux of > 100 / cm^2 / sec into an area of 5 cm^2
- minimal space in test beam hall: a 1 m^2 table just below the beamline
- a BM 109 for Lorentz angle drift studies
- in the beam we need to locate a scintillator trigger, 8 planes of silicon strip detectors for precision tracking and several planes of diamond detectors under test
- the above items represent a total of about 6% X_o
- No significant electronics space is needed near the beamline. Some rack and table space is needed in a nearby counting room
- Cabling to the counting room is also quite minimal

Due to the expected increase in new diamond material, we are requesting 3 runs spread out over the 1999 Fixed-Target running period consisting of 5 days of beam time/run with occasional beamline access every 8 hours. We will be ready for beam in May of 1999.

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