Disclaimer

D0 note 2665

Efficiency and Resolution of a Scintillating Fiber Doublet

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1 Introduction

The central tracking system will be completely replaced in the upgrade of the D0 detector planned for collider run II[1]. The new tracker will consist of a solenoidal magnet, a silicon microstrip inner tracker and a scintillating fiber outer tracker. In order to minimize the cost and the amount of material, the number of measurements is fairly small. Consequently, each detection element must provide a precise measurement with high efficiency.

The active element of the outer tracker is the scintillating fiber. The fibers have a circular cross section and are made up of an active (scintillating) core and an inactive cladding which traps the light and protects the core. Present plans call for and active diameter of 770 μm and an overall diameter of 870 μm.

The basic detection element of the scintillating fiber system is the fiber doublet. A ribbon is a sheet of uniformly spaced parallel fibers. A doublet consists of two parallel ribbons with fibers offset by a half fiber spacing so that the fibers in one layer lie in front of the gaps in the other (see figure 1-1). This arrangement reduces or eliminates the inherent inefficiency of a single ribbon due to the gaps between active fiber elements.

We have carried out simulation studies to evaluate the efficiency and resolution of a scintillating fiber doublet. The efficiency is the probability that a track crossing the doublet will produce a signal. The resolution reflects the deviation between the measured and true position. (This position is measured in the direction in the plane of the ribbons and perpendicular to the fibers.)

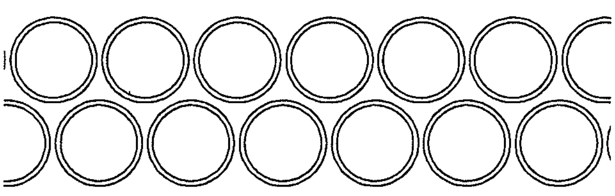

Figure 1-1. Cross section of a scintillating fiber doublet.

The efficiency and resolution have been evaluated for various geometries and assumptions about the response of the system. Considerable attention is paid to the fiber spacing which is important for both efficiency and resolution. We also discuss the effect of modifying the spacing between the two ribbons in a doublet. The most important parameter in the response is the mean number of detected photons which is varied over a wide range. Different fiber signal thresholds are studied. We also consider the effects of both dead and noisy channels.

2 Simulation

The simulation was carried out in a fairly simple framework called SFSIM that was created for this purpose. There is an initialization stage in which one or more doublets of fibers are positioned inside a global volume followed by a loop over a large number of events (typically 10000). In each event, a track is generated and propagated through the volume. The response of the fibers is evaluated and then the data from the fibers is used to evaluate the measured position. The true position of the track and the nearest measured position are recorded for each doublet.

The tracks are generated in a plane perpendicular to the fibers; *i.e.* the plane of figure 1-1. The position parallel to fibers is chosen from a flat random distribution which includes an integral number of fibers. The angle between the track direction and the normal to the ribbons is denoted by α and is chosen from a flat distribution over a specified range. Typically this range was chosen to be $-0.015 < \alpha < 0.015$ rad. The limits of this range correspond to the angle of a track with a transverse momentum of 10 GeV/c at the outer radius of the D0 tracking system.

The tracks are propagated along straight lines and the positions at which they enter and exit the global volume are recorded. Curvature, multiple scattering and other interactions are deliberately neglected because they are not expected to be important in characterizing the response of a doublet. These effects will be important in characterizing the overall tracking system.

The SFT package[2] is used to evaluate the response of the fibers based on the positions at which the track enters and exits the volume. The expected number of detected photons is proportional to the path length through the active part of the fiber. The actual number is obtained by selecting from the corresponding Poisson distribution. This number is smeared with a Gaussian of (width 0.2 times the mean) to generate the observed signal. A typical distribution is shown in figure 2-1. A fiber is hit if this signal is above an adjustable threshold for which we used values of 0.5 and 1.5 photons. SFT also allows the user to randomly enable or disable some fraction of the channels. Randomly enabled channels correspond to noise which might arise from prompt tracks, light leaks, electronic jitter, tails of previous events or other sources.

Having generated a list of hit fibers, the next step is to cluster nearby fibers to evaluate hit positions. For this we used the clustering part of TRF[3,4]. Adjacent hit fibers within a layer are clustered together and then these are clustered with any overlapping clusters in the other layer. (More precisely, FIBSEP[3] is left at its default value of 0.6.) The position of the hit is the center of this cluster.

In the next stage, data is written out for later analysis. These data include the generated track parameters, the expected position at the doublet and the position of the hit nearest this position.

3 Analysis

The performance of the system is characterized by the efficiency and resolution. For those runs without noise, this characterization is straightforward. The efficiency is the fraction of tracks for which one or more fibers are hit. There will be only one hit in each doublet and the deviation for that event is the difference between the position of that hit and the prediction.

The resolution is characterized by giving the root mean square deviation but it should be kept in mind that these distributions are far from being Gaussian. We are assuming the active fiber diameter is 770 μm. If this diameter (and the spacings) are changed by some factor, then the resolution will change by the same factor.

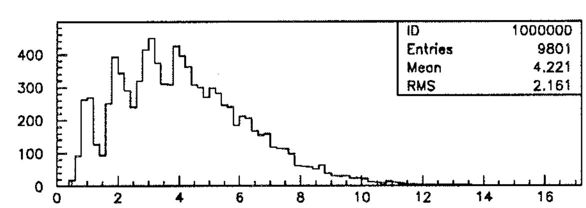

Figure 2-1. Typical distribution for the total signal from a doublet at a very low light level.

4 Geometry

The active fiber diameter is denoted d, the center-to-center spacing between fibers in a layer is s and the center-to-center spacing between ribbons is denoted w. These three parameters characterize the internal geometry of a fiber doublet. It is also convenient to introduce u which is the center-to-center spacing between adjacent fibers in different ribbons. Clearly u satisfies

$$u^2 = d^2 + s^2/4.$$

In order to maintain the scaling between the resolution and the active fiber diameter, we will only speak of the ratios s/d and u/d. Due to the cladding, the minimum possible value for each of these ratios is 1.13 corresponding to a close packing of the fibers.

We fix u/d to this minimal value because pulling the layers apart is not expected to improve the efficiency or resolution. We expect inefficiencies at angles of incidence such that the gaps in one layer line up with those in the next. Increasing the layer and/or fiber spacings will increase the size of this effect and cause it to occur at smaller (more important) angles of incidence.

5 Angle of incidence

Figure 5-1 shows the resolution of a doublet as a function of the incident angle α under near-ideal conditions. The fibers are close packed (s/d = 1.13), the brightness is high (17.4 photons) and there are no dead or noisy channels. The largest angle plotted (0.5 rad) corresponds to a transverse momentum of approximately 300 MeV/c. The resolution degrades rapidly with increasing angle of incidence because the gaps in one

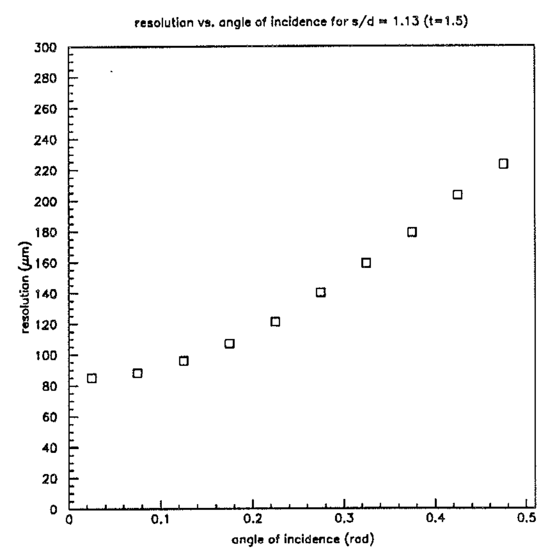

Figure 5-1. Resolution as a function of incident angle for close packing (s/d = 1.13), high brightness (17.4 photons) and no dead or noisy channels.

layer no longer line up with the fibers in the other when tracks approach with a non-zero angle.

For transverse momenta at or below about 10 GeV/c, multiple scattering will be more important than the detector resolution in limiting the precision to which we measure the track parameters. For this reason and because higher transverse momentum tracks are often inherently more interesting, we will focus on tracks above that momentum threshold for the rest of our discussion.

6 Brightness and threshold

One of the most important parameters of the scintillating fiber system is the mean number of detected photons. Clearly this depends directly on the active diameter d but it also depends weakly on the spacing ratios s/d and u/d which open up gaps when they are increased. It will also depend on the angle of incidence, threshold and the fractions of dead and noisy channels. In order to make fair comparisons, we define the brightness to be the mean number of detected photons that would be detected for fixed conditions: close-packed fibers, zero angle of incidence, threshold of 0.5 and no dead or noisy channels. The brightness was measured to be 19.2 photons/doublet in the D0 cosmic ray beam test[5].

Considerable effort has been expended to obtain this value for the brightness and we assume it will not increase further unless the active diameter is increased. However, the transition to the large scale full detector and degradation with time (including radiation damage) may well lead to smaller values and it is important to understand how the performance of a doublet degrades as the brightness decreases.

Figure 6-1 shows the doublet efficiency and resolution as function of brightness for thresholds of 1.5 and 0.5 photons. The performance starts to degrade at a brightness of 10 photons/doublet for a threshold of 1.5 photons and at 6 photons/doublet for a threshold of 0.5 photons. Thus we have a safety factor of about two at the higher threshold and almost another factor of two if the threshold is decreased.

For the remainder of this paper, we assume a threshold of 1.5 photons. This is done for definiteness and because of concern that there may be a high level of noise at the single photon level. Figure 6-1 indicates that similar performance will be observed for a threshold of 0.5 photons when the brightness is decreased by 40-50%.

7 Resolution

In the above discussion, the position resolution was characterized by a single parameter—the root mean square deviation. Figure 7-1 shows the distributions for various light levels and it is evident that they are far from Gaussian. In the ideal (high brightness) case, the resolution is seen to be the sum of two square distributions: the broader corresponds to tracks crossing a fiber in each layer and the narrower to tracks which cross a gap in one of the layers. As the performance degrades (decreasing brightness), long tails appear. Tails like these may cause problems in finding and fitting tracks well beyond that which would result from a simple broadening of the distribution.

8 Spacing

The next question we address is how to choose the fiber spacing for a fixed active diameter. The cost of the system is largely proportional to the channel count which depends inversely on s/d so there is considerable motivation to increase this value if the performance improves or remains constant. At high light levels (brightness above 10), the efficiency will not be much affected as long as s/d is around or below 1.5.

We do, however, expect the resolution to change with spacing. We can easily calculate the resolution if we assume a simple model in which a track crossing any part of an active fiber produces a hit. If we could remove the cladding and close pack the fibers, then $s/d = 1.0$ and a track will always cross a fiber in both layers. The fiber in the second layer indicates which half of the fiber in the first layer has been hit. Thus we have an effective bin size of $d/2$ and the resolution is $(d/2)/\sqrt{12} = 111\ \mu m$. As the spacing is increased, a

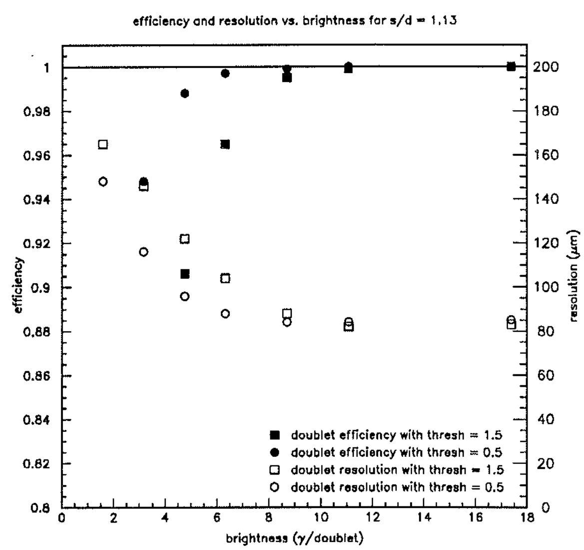

Figure 6-1. Efficiency (filled) and resolution (open) as a function of brightness for thresholds of 1.5 (squares) and 0.5 (circles) photons. Fibers are close-packed ($s/d = 1.13$), $|\alpha| < 0.015$ and there are no dead or noisy channels.

gap opens up between the fibers and the fiber is broken up into three bins with the absence of a hit in the second layer indicating a track has passed near the center of the fiber in the first. The optimal resolution is obtained when these bins are of equal size, *i.e.*, when $s/d = 4/3$. In this case, the resolution is $(d/3)/\sqrt{12} = 74\ \mu m$.

Figure 8-1 shows the efficiency and resolution as a function of *s/d* for a high light level and two low levels. At the high brightness, we see that, as expected, there is a broad minimum around 1.3 corresponding to a resolution of 74 μm and the efficiency is always 100%.

At low light levels, it becomes possible for a track to have a significant path length in a fiber core without

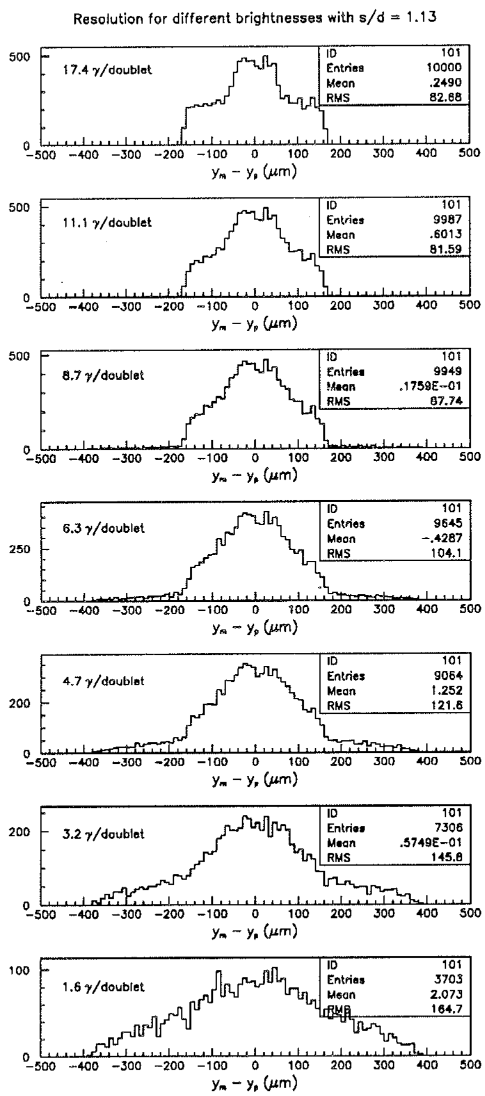

Figure 7-1. Resolution distributions (difference between measured and predicted position) for brightness varying from 17.4 to 1.6 photons/doublet. Fibers are close packed ($s/d = 1.13$) and the threshold is 1.5 photons. There are no dead or noisy channels.

triggering. In this case, the efficiency will fall from unity with the value getting smaller as the spacing is increased. The assumption that a missed layer corresponds to a gap between fibers becomes less reliable and there is little or no advantage to have *s/d* around 1.3 Figure 8-1 shows that, at low light levels, the best efficiency and resolution are obtained with the closest packing (smallest *s/d*).

Thus, we see that *s/d* around 1.3 provides the best resolution under ideal conditions but close packing is more robust against a decrease in brightness. We will return to this theme as we look at two other important effects which degrade the performance: dead channels and noise.

9 Dead channels

We will have to tolerate some fraction of dead channels in out system due to the high cost associated with opening the detector to make repairs. Figure 9-1 shows the efficiency and resolution as a function of the fraction of dead channels up to 0.05. Results are presented for the close packed and optimal resolution spacings, *i.e.*, s/d = 1.13 and 1.3, respectively.

For these small fractions of dead channels, we expect that most of the inefficiency comes from a track crossing a gap in one layer and a dead channel in the next. For infinitely bright fibers, this leads to a doublet efficiency of

$$\varepsilon = 1 - 2\,(1 - d/s)\,f_{dead}.$$

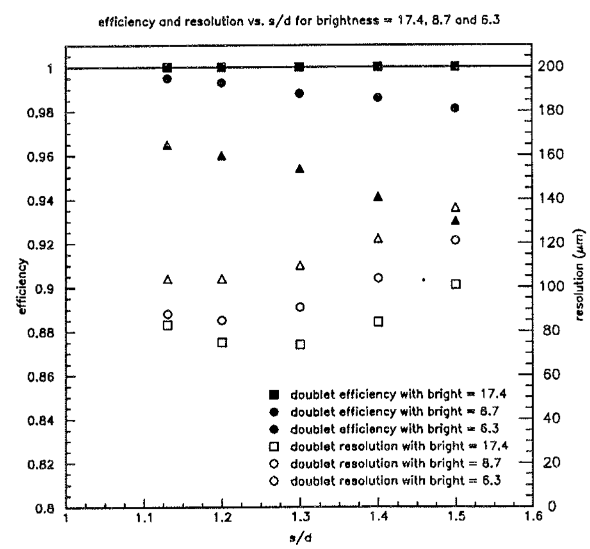

Figure 8-1. Efficiency (filled) and resolution (open) as a function of *s/d* for brightness (at $s/d = 1.13$) of 17.4 (squares), 8.7 (circles) and 6.3 (triangles) γ/doublet. The incident tracks have $|\alpha| < 0.015$ and there are no dead or noisy channels. The threshold is 1.5 photons.

This prediction is shown in the figure. The results are slightly worse presumably due to inefficiencies at the edges of the fibers.

The resolution increases as a function of dead channel fraction at the rate 4 μm/% for both spacings. The spacing $s/d = 1.3$ retains its resolution advantage over the range.

Obviously, we would like to minimize the number of dead channels. There is a significant degradation in both efficiency and resolution even at 1-2% dead channels. If channels are known to be dead, then the efficiency can be recovered by treating all such channels as if they were on. They then become noise channels. The effect of these is discussed in a later section.

10 Good clusters

Before examining the effect of noise, we pause to introduce the concept of a good cluster. A good cluster is one which includes at most one fiber in each layer. In the absence of noise, tracks at or anywhere near normal incidence will fall into this category. Once noise is introduced, a fiber adjacent to a hit fiber may also fire and broaden the cluster. If the broadened cluster has more than one hit in a plane, then it is flagged as a wide cluster and is assigned a much larger position uncertainty.

The good-cluster efficiency is defined to be the fraction of incident tracks which produce a good cluster. We will refer to our earlier definition as the simple efficiency to distinguish it. The good-cluster resolution is the root-mean-square position deviation for the good clusters.

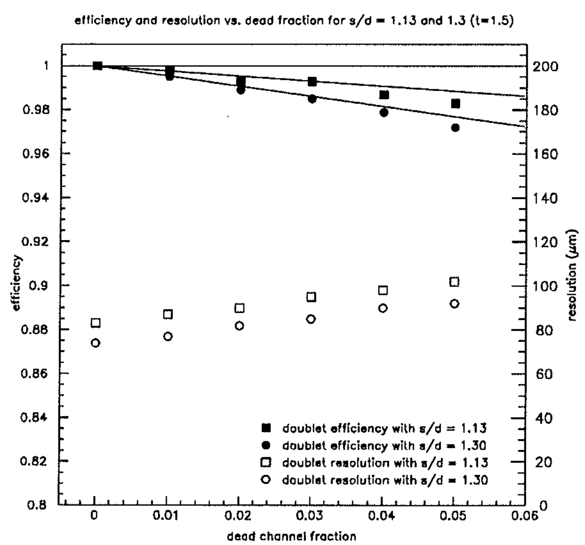

Figure 9-1. Efficiency (filled) and resolution (open) as a function of the fraction of non-operational channels for $s/d = 1.13$ (squares) and 1.30 (circles). The brightness is high (17.4), the threshold is 1.5 γ and there is no noise. The curves are the efficiency predictions discussed in the test.

The resolution for all clusters is called the simple resolution.

Note that wide clusters which do not contribute to the good-cluster efficiency will still contribute to the simple efficiency and will be useful for track finding. However, they are considerably less precise and will generally be much less useful for pinning down the track kinematics.

11 Noise

For the purpose of our studies, a noisy channel is any channel which is on due to any source other than the track of interest. In the real detector, sources of noise include other prompt tracks, delta rays, electronic jitter, tails of signals from earlier crossings, *etc.* Here, we generate noise by randomly turning on some fraction of channels.

We slightly modify our definition of efficiency (both simple and good-cluster) by adding the requirement that the cluster be within 1 mm of the track crossing. This is done so that a distant unrelated noise hit does not substitute for an inefficiency. This has no effect on any of the earlier results because they had no noise.

Figure 11-1 shows the simple efficiency, good-cluster efficiency and good-cluster resolution as a function of the fraction of noise channels. Results are shown for the usual two spacings: close packed ($s/d = 1.13$) and optimal resolution ($s/d = 1.30$). The efficiency is always near unity because the light level is high and there are no dead channels. There is a slight decrease at high noise as a few clusters are pulled more than a millimeter from the track position.

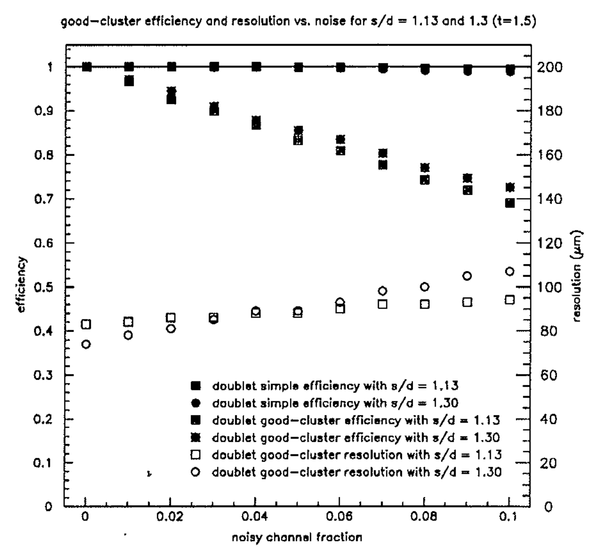

Figure 11-1. Simple efficiency (filled), good cluster efficiency (crossed) and good-cluster resolution (open) as a function of noise for $s/d =$ 1.13 (squares) and 1.30 (circles). The brightness is high (17.4) and there are no dead channels. The threshold is 1.5 photons.

The good-cluster efficiency falls smoothly from 1.0 to about 0.7 as the occupancy (fraction of noise channels) is increased from 0 to 10%. The results are similar for the two spacings with the good-cluster efficiency slightly lower for the closer spacing.

The good-cluster resolution degrades in both cases but it degrades much faster for the wide spacing. The wide spacing provides 9 μm better resolution with no noise (74 *vs.* 83 μm) but is 13 μm worse at 10% noise (107 *vs.* 94 μm).

The change with spacing is expected because a doublet with greater spacing has more single-hit clusters (*i.e.* a hit in one layer and gap in the other) while one with closer spacing has more double-hit clusters (one hit in each layer). When noise is adjacent to a double hit cluster, it is no longer good and thus the good-cluster efficiency falls but the good-cluster resolution is not affected. However, when there is a single noise hit in the gap layer of a single-hit cluster, it becomes a double-hit cluster and still appears to be good but its position is significantly altered. Thus the good-cluster efficiency is higher but the good-cluster resolution is degraded. The increase in good-cluster efficiency with increased spacing is actually a bad thing because the difference is due to clusters with very poor position measurements.

12 Conclusions

The scintillating fiber doublet can provide the precise and efficient measurements required for the D0 upgrade tracking system but there are many caveats to consider.

Number one is the brightness. The results from the cosmic ray test are very encouraging and appear to offer a factor of two safety margin. If the performance is unexpectedly worse or degrades with time, decreasing the threshold from 1.5 to 0.5 photons will allow another 40% decrease in the light level. However, this may substantially increase the noise.

It is clearly desirable to keep the fraction of dead channels at or below 1%. The degradation in efficiency and resolution is slow but steady as this fraction is increased.

It would also be ideal to keep the noise at a similar level but we expect occupancies of a few percent just from other prompt tracks. Figure 11-1 indicates that the price we pay for this noise is a loss of precision measurements which will degrade our measurements of the track parameters. The loss is linear with about 30% of the precision measurements (good-clusters) lost at an occupancy of 10%. Noise in the detector also complicates the pattern recognition forcing compromises which can lead to decreased track-finding efficiency.

It is clear that we would like to maximize the brightness and minimize the fractions of dead and noisy channels.

The fiber spacing is a more subtle question. Under ideal conditions, a fiber spacing around $s/d = 1.3$ can improve the resolution by using the information from gaps between fibers. It also significantly reduces the channel count and hence the cost of the system. However, the price we pay is a loss in robustness. The efficiency drops faster as the brightness decreases or the fraction of dead channels increases. Perhaps most dramatic is the good-cluster resolution as a function of noise. This resolution degrades much more quickly at the larger spacing.

Figure 12-1 shows the simple efficiency, good-cluster efficiency and good-cluster resolution as a function of spacing under more realistic conditions. The brightness is high but 1% of the channels are dead and 5% are noisy. The simple efficiency decreases with spacing due to the dead channels. The resolution is flat up to $s/d = 1.3$ rather than showing the improvement observed for ideal conditions. This and the fact that the good-cluster efficiency increases over the same range indicate that clusters with large deviations are being added to the sample. This is demonstrated by figure 12-2 which shows the resolution distribution for each of the points in figure 12-1. As expected, the tails become more pronounced as the spacing is increased.

For these reasons, we conclude that the close-packed spacing would be best for the conditions under which D0 is expected to operate. The small gain in resolution under ideal conditions (central peaks in figure 12-2) is not worth the possible degradation due to reduced brightness or increased noise (tails in the figure).

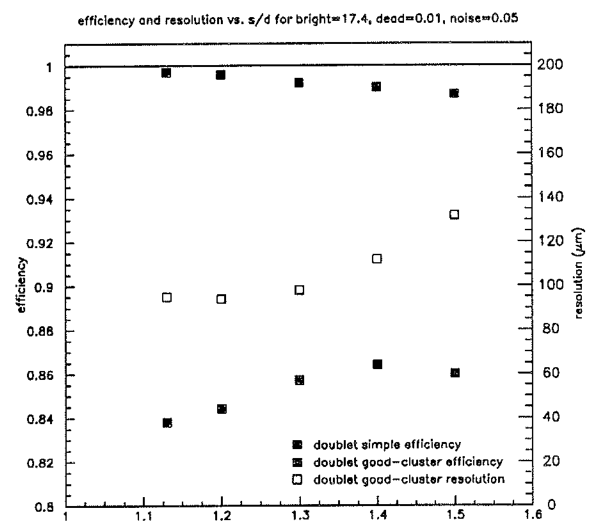

Figure 12-1. Simple efficiency (filled), good-cluster efficiency (crossed) and good-cluster resolution (open) as a function of *s/d* for high brightness (17.4 photons) with 1% dead channels and 5% noisy channels. The threshold is 1.5 photons.

References

1. The D0 Collaboration, *The D0 Upgrade*, D0 note 2542.

2. D. L. Adams, *SFT Programmer's Manual*, anonymous FTP from bonner-ibm1.rice.edu in pub/adams/sft.

3. D. L. Adams, *TRF User's Manual*, anonymous FTP from bonner-ibm1.rice.edu in pub/adams/trf.

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5. D. Adams *et al.*, *Performance of a Large Scale Scintillating Fiber Tracker using VLPC Readout*, D0 note 2280.

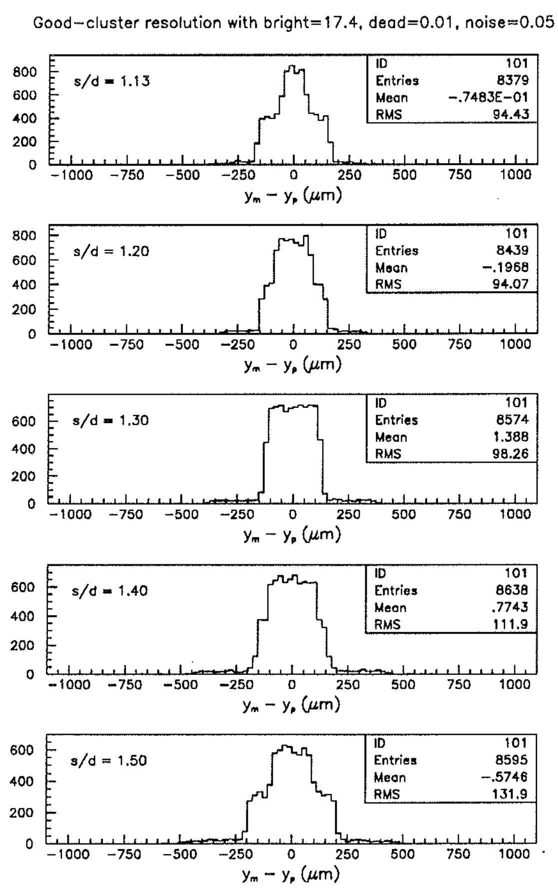

Figure 12-2. Good-cluster resolution distributions corresponding to the points in figure 12-1.