SDC-92-279

SDC
SOLENOIDAL DETECTOR NOTES

EFFICIENCY AND RESOLUTION OF A DOUBLE-LAYER OF SCINTILLATING FIBERS

June 18, 1992

David L. Adams
Rice University

SDC-92-279
D0 note 1437

Efficiency and Resolution of a Double-layer of Scintillating Fibers

David L. Adams
Rice University

June 18, 1992

The response of a double-layer of scintillating fibers has been modeled to provide estimates of the tracking efficiency and resolution as a function of the incident angle of a charged track. The geometry is characterized by the fiber and layer spacings and the fiber response is characterized by the mean number of photons, the single-photon detection efficiency and the fraction of dead channels. Each of these parameters is varied to assess their impact on the efficiency and resolution.

Introduction

Scintillating fiber tracking systems have been proposed for the SDC detector at SSC [1,2] and the D0 detector at Fermilab [3]. The major motivation in both cases is the low occupancy made possible by the granularity and intrinsically fast response of a fiber system. Both detector groups also share the concern that too small a number of detected photons may lead to inefficiencies and degraded position resolution.

Although a few thousand scintillation photons are created when a minimum-ionizing particle crosses the center of a fiber, only a few percent are captured by the fiber. A large fraction of these may be attenuated as they travel down the fiber, can be lost at couplings or may not be detected due to inefficiencies in the photodetector. Consequently, it is of great interest to know what minimum number of photons must be detected for the detector to remain viable.

Here we make simplifying assumptions about the single fiber response and introduce parameters to describe the geometry and likelihood for photon detection. The efficiency and position resolution are calculated for various values of these parameters.

Geometry

A double-layer of fibers is made up of two layers of fibers offset by one half spacing so that the center of a fiber in one layer lies directly in front of the gap between fibers in the other. The spacing between adjacent fibers in a layer is denoted by s and the distance between the centers of the two layers by w. The active fiber diameter is denoted by d. Note that the fibers are typically clad with a non-scintillating material which is not included in this diameter.

In our model, only the relative dimensions are relevant and we will express all dimensions relative to the active fiber diameter. Thus, the two variable geometrical parameters are the relative fiber spacing s/d and the relative plane spacing w/d. The relative fiber spacing must be greater than one to allow for the cladding and fiber-to-fiber diameter variations (neglected here). The relative layer spacing can in principle be less than one because the fibers in one plane sit in the gaps in the other but construction techniques may require a larger value. The present design value for the SDC is $d = 925\ \mu m$.

Fiber response

The fiber and photodetector response is mainly characterized by the parameter n_0 which is the mean number of photons detected when a track crosses through the center of a fiber. If a track does not cross through the center, the mean number is reduced in proportion to the track path length through the active fiber. The actual number of detected photons is assumed to follow a Poisson distribution about this mean.

The readout is assumed to be a simple yes/no which indicates whether or not each fiber fired. If no photons are detected, the fiber does not fire while if two or more photons are detected, then the fiber always fires. For the case of a single detected photon, we introduce the inefficiency A_1 which is the probability that the fiber will not fire. This parameter is the fraction of singe-photon signals which fall below the discriminator threshold. Table 1 gives the probability to detect zero, one or more than one photon for various mean numbers of detected photons.

Finally to get some feeling for the robustness of the system we introduce f_{dead} which is the fraction of chan-

<n>	P(n=0)	P(n=1)	P(n>1)
0	1.00	0.00	0.00
1	0.37	0.37	0.26
2	0.14	0.27	0.59
3	0.05	0.15	0.80
4	0.02	0.07	0.91
5	0.01	0.03	0.96

Table 1. Probability of detecting zero, one or more than one photon for various mean numbers of photons. The distribution is Poisson.

nels which never respond. These are assumed to be distributed randomly.

Default parameters

We have introduced five parameters to characterize the response of a double-layer. It is not practical to vary all five simultaneously, so we define default values for each. The relative fiber spacing s/d is chosen to be 1.1 to allow for up to 7% cladding thickness and 3% size variations. The relative layer spacing s/d is also 1.1 allowing for a thin layer of glue between the fiber layers.

The inefficiency for detecting a single photon, A_1, is chosen to be 0.3. Note that figure 4-72 in [1] shows a very good separation between the noise and single photon peak suggesting that a smaller value may be realized.

Table 4-21 in [1] gives the minimum average number of photons expected for the SDC. This average value $\langle n \rangle$ is related to value obtained when a track crosses the center of the fiber, n_0, by

$$n_0 = (4/\pi)\,(s/d)\,\langle n \rangle$$

If we assume a relative spacing of 1.1, the expected minimum SDC average $\langle n \rangle = 4.5$ corresponds to $n_0 = 6.3$ and we adopt 6.0 as our default value for this parameter. Note that this value is for the center of the detector where the smallest amount of light is produced and the attenuation is greatest.

No large-scale fiber tracking tests have yet been carried out so it is difficult to assess what fraction of channels will fail. We assign a default value of $f_{dead} = 0.01$ but hope to do better in the final detector.

Track parameters

There are two parameters that characterize the incident track. They are the position and angle normal to the fibers. Although the coordinate and direction along the fiber greatly influence the number of photons detected, we include this effect by varying n_0.

The track position, x_t, will obviously have a dramatic effect on the amount of light detected since a track may pass through most of the fiber or in the gap between fibers. Rather than evaluating the performance as a function of position, we average over all positions when calculating the efficiency and position resolution.

The track direction, α, plays an important role because of the correlation between the two layers. The gaps in one layer are lined up with the fibers in the second so that the efficiency and resolution are optimized for tracks at normal incidence. This is the most interesting case for us because the SDC and D0 detectors are cylindrical and high-p_T tracks from the beamline will cross the fiber layers at normal incidence. As the momentum decreases, the angle of incidence increases and the efficiency and resolution will eventually be degraded.

For a cylindrical detector in a 2 Tesla field, the angle of incidence is related to the transverse momentum, p_T, and the transverse radius, r, by

$$\sin\alpha = (0.003\ \mathrm{GeV/c/cm})\,\frac{r}{p_T}.$$

Table 2 lists some values of the angle relevant to the SDC with inner layer at 60 cm and outer layer at 165 cm and to D0 with inner layer at 20 cm and outer layer at 54 cm.

Performance evaluation

The performance of the double-layer is characterized by calculating the efficiency and position resolution. The efficiency is the probability that at least one fiber fires when a track crosses the superlayer. The criteria for a fiber to fire are defined in the section on fiber response. The position resolution is the root-mean-square difference between the measured and true positions evaluated midway between the two layers. The measured position is obtained by averaging over the positions of all fibers that fire. Both quantities are averaged over x_t and plotted as a function of α. The position resolution scales with the fiber size so we evaluate the relative position resolu-

p_T (GeV/c)	α(r=20)	α(r=60)	α(r=165)
0.5	6.9	21.1	81.9
1.0	3.4	10.4	29.7
2.0	1.7	5.2	14.3
5.0	0.7	2.1	5.7

Table 2. Angle of incidence (degrees) for tracks of various p_T on a cylindrical detector in a 2.0 Tesla field. The last two columns correspond to the inner and outer SDC superlayers. The r=20 entry is the inner layer of the D0 detector and the outer layer of that detector is near r=60.

tion, σ_x/d, which must be multiplied by the fiber diameter to obtain the absolute resolution.

Fiber spacing

The default value, $s = 1.1\ d$, for the fiber spacing is about the smallest possible allowing for cladding and fiber-to-fiber diameter variations. Although increasing the spacing can be expected to decrease the efficiency, it has the potential to reduce the cost and material. These are both very important considerations.

Figure 1 shows the efficiency obtained when the spacing is varied from 1.0 to 1.5 times the active fiber diameter. The efficiency at normal incidence ($\alpha = 0$) varies smoothly from 0.998 to 0.986 with the default spacing ($s/d = 1.1$) providing an efficiency of 0.995. At 25 to 30 degrees incident angle, the gaps in the two layers line up and the efficiency is degraded significantly for spacings above the default value.

The position resolution over the same range of spacings is shown in figure 2. Near normal incidence, spacings $s/d = 1.1$ - 1.2 give optimal resolution of $\sigma_x/d = 0.129$ corresponding to $\sigma_x = 119\ \mu m$ for 925 μm fibers. The resolution near normal incidence is degraded slightly for other values of the spacing. The resolution is degraded significantly when the fibers in the two layers line up at 25 to 30 degrees incident angle. This is not a serious concern because these angles correspond to low momentum tracks for which the tracking resolutions will be limited by multiple scattering rather than position resolution.

Layer spacing

The only motivation for increasing the spacing between the two layers is for convenience in construction. Here we study different values to understand the size of the effect but expect to build a value near the default of $w/d = 1.1$. Figures 3 and 4 show the efficiency and position resolution for layer spacings from $w = d$ to $1.5\ d$. The effects are not very dramatic but there is some degradation of the efficiency and resolution around 20 - 25 degrees incident angle. Again this is the angle where the fibers from one layer line up with those in the next. As expected, both efficiency and resolution become worse as the spacing is increased.

Single photon inefficiency

Figures 5 and 6 show the efficiency and position resolution obtained when the single photon inefficiency is varied from 0.0 to 0.5. At normal incidence, the track efficiency falls from 0.997 to 0.994 and the resolution is unaffected. This parameter is, of course, only important for low light levels and we expect more significant effects if the photon count falls below the default value

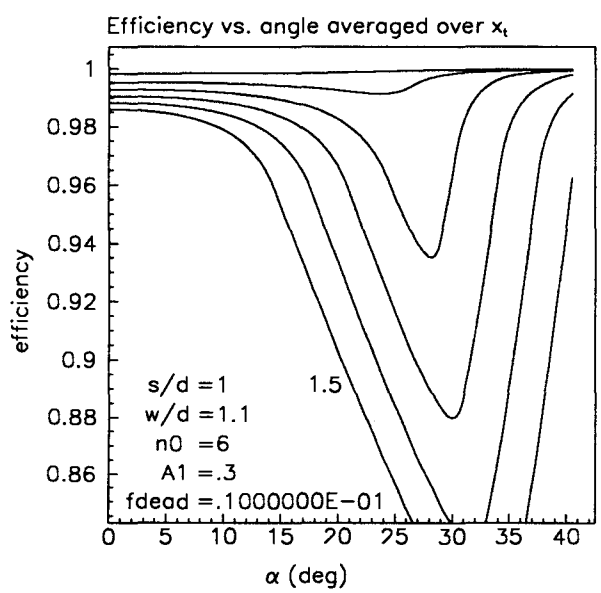

Figure 1. Two-layer efficiency as function of the angle of incidence. The different curves are different values of the relative fiber spacing. The values are s/d = 1.0, 1.1, 1.2, 1.3, 1.4 and 1.5 from top to bottom. The other parameters are fixed at their default values. The default value $s/d = 1.1$ is the second curve from the top.

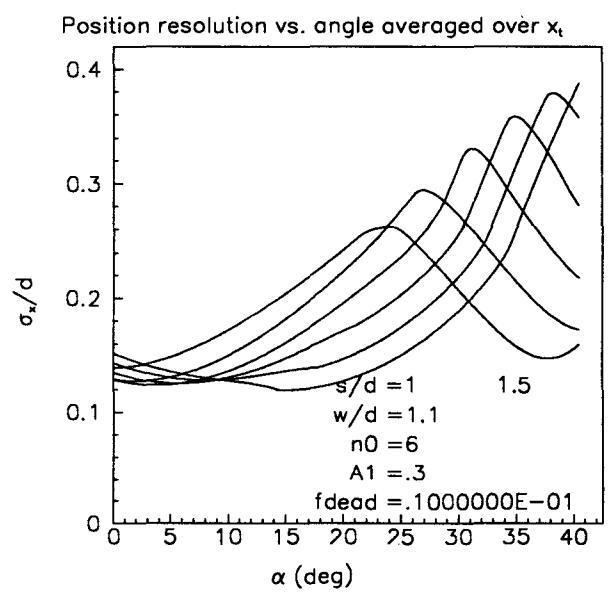

Figure 2. Position resolution as a function of the angle of incidence. The different curves are for different values of the relative fiber spacing. The values are $s/d = 1.0$, 1.1, 1.2, 1.3, 1.4 and 1.5 from bottom to top on the right hand side of the figure. All other parameters are fixed at their default values. The default value $s/d = 1.1$ is the curve second from the bottom on the right-hand side of the figure.

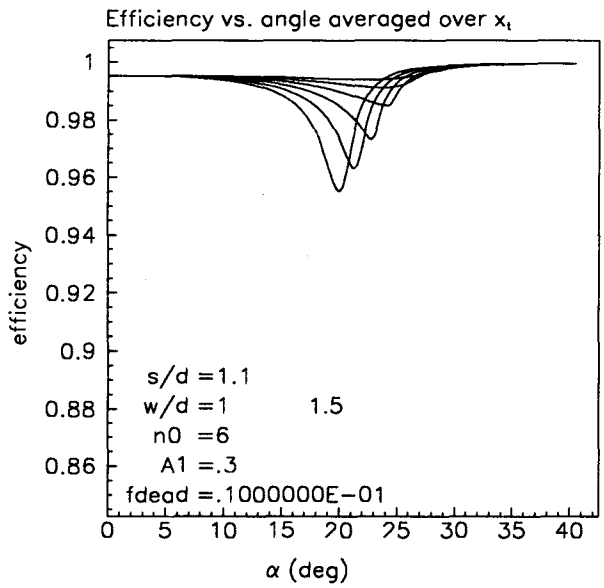

Figure 3. Two-layer efficiency as function of the angle of incidence. The different curves are different values of the relative layer spacing. The values are w/d = 1.0, 1.1, 1.2, 1.3, 1.4 and 1.5 from top to bottom below 20 degrees. The other parameters are fixed at their default values. The default value w/d = 1.1 is the curve second from the top at 20 degrees.

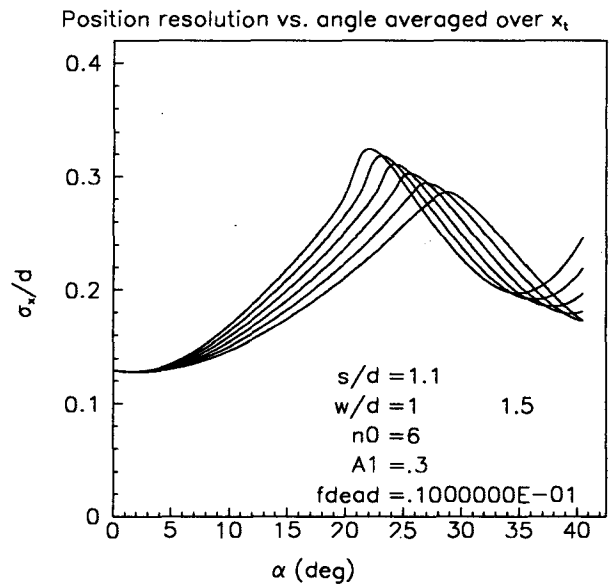

Figure 4. Position resolution as a function of the angle of incidence. The different curves are for different values of the relative layer spacing. The values are w/d = 1.0, 1.1, 1.2, 1.3, 1.4 and 1.5 from bottom to top below 20 degrees. All other parameters are fixed at their default values. The default value w/d = 1.1 is the curve second from the bottom at 20 degrees.

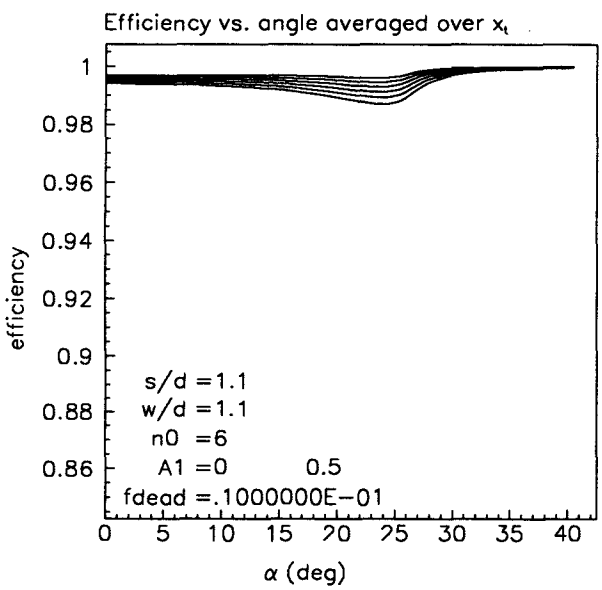

Figure 5. Two-layer efficiency as function of the angle of incidence. The different curves are different values of the single photon inefficiency. The values are A_1 = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5 from top to bottom. The other parameters are fixed at their default values. The default value A_1 = 0.3 is the curve third from the bottom.

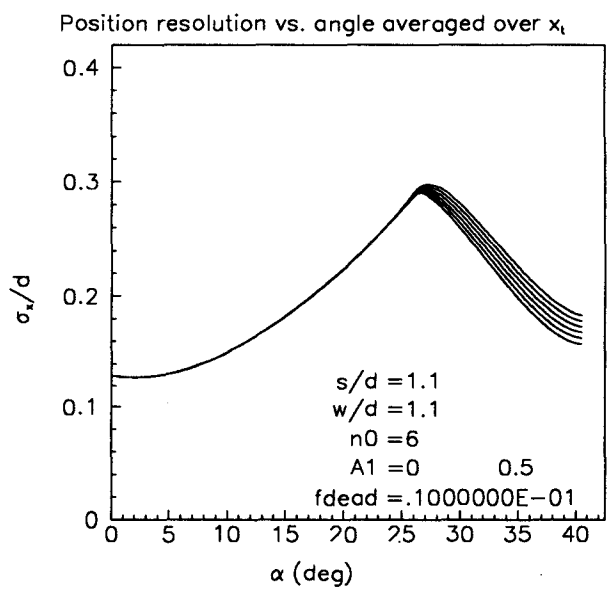

Figure 6. Position resolution as function of the angle of incidence. The different curves are different values of the single photon inefficiency. The values are A_1 = 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5 from bottom to top. The other parameters are fixed at their default values. The default value A_1 = 0.3 is the curve third from the top.

$n_0 = 6.0$. Conversely, this parameter plays no role if the photon count is significantly higher.

Photon count

The parameter that has the greatest effect on the double-layer performance is the single-fiber light output. We have characterized this in terms of the mean number of photons detected when a track crosses the center of a fiber. One of the most important goals of this study is to understand the double-layer performance at low light levels.

Figure 7 show the two-layer efficiency as a function of incident angle for a range of light levels: $n_0 = 2.0$, 3.0, . . , 10.0. The efficiency increases significantly with the photon count until this count reaches 6-7 after which there is little gain. Note that this saturation point corresponds to an average response of $\langle n \rangle = 4$-5, precisely the minimum expected for SDC. However, the efficiency remains above 0.98 even for $n_0 = 3.0$ ($\langle n \rangle = 2.1$) indicating that significantly lower light levels could be tolerated.

Figure 8 shows the position resolution over the same range of photon counts. For normal incidence, the resolution is essentially constant above $n_0 = 6$ and is only degraded by 23% at $n_0 = 3.0$ ($\langle n \rangle = 2.1$). The resolution for high photon counts is $\sigma_x/d = 0.128$ which gives $\sigma_x = 118$ μm for the 925 μm fibers planned for the SDC.

Dead Channels

Finally we consider the effect of randomly distributed dead channels. Figures 9 and 10 show the efficiency and position resolution for zero up to 5% dead channels. At normal incidence, the efficiency is 0.998 with no dead channels decreasing to 0.982 with 5% of the channels dead. The position resolution degrades by only 15% over this same range.

Conclusions

With our default parameters, a double-layer of scintillating fibers is a very effective component of a charged particle tracking system. At normal incidence, the efficiency is 0.995 and the position resolution is better than 120 μm. The system is robust in that it continues to function even if one of the fiber response parameters falls below our expectations. If the number of detected photons falls to half the expected value or if the fraction of dead channels is as high as 5%, we still obtain an efficiency of 0.98 and the position resolution is degraded by about 20%. More serious problems may occur if both parameters are worse than expected. Also, the single-photon efficiency can play a more important

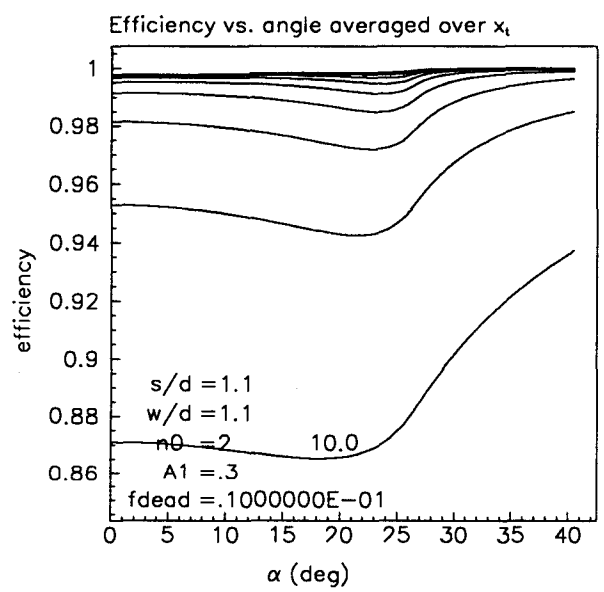

Figure 7. Two-layer efficiency as function of the angle of incidence. The different curves are different values of the mean photon count for a track crossing the center of the fiber. The values are $n_0 = 2.0, 3.0, \ldots, 10.0$ from bottom to top. The other parameters are fixed at their default values. The default value $n_0 = 6$ is the curve fifth from the bottom.

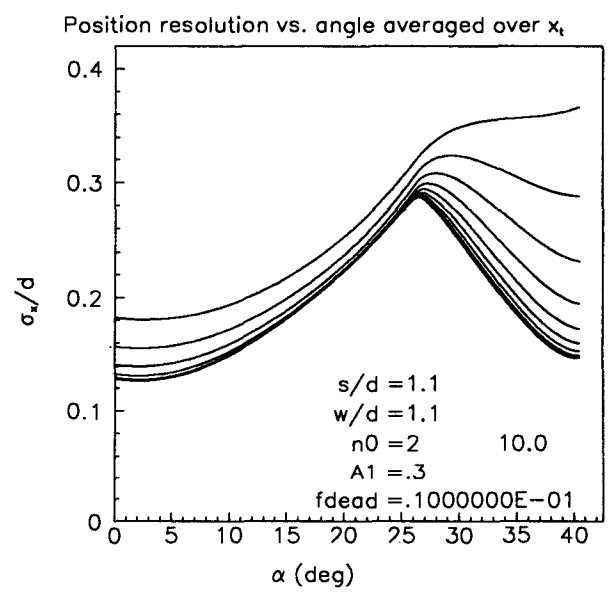

Figure 8. Position resolution as a function of the angle of incidence. The different curves are for different values of the mean photon count for a track crossing the center of the fiber. The values are $n_0 = 2.0, 3.0, \ldots, 10.0$ from top to bottom. All other parameters are fixed at their default values. The default value $n_0 = 6$ is the curve fifth from the top.

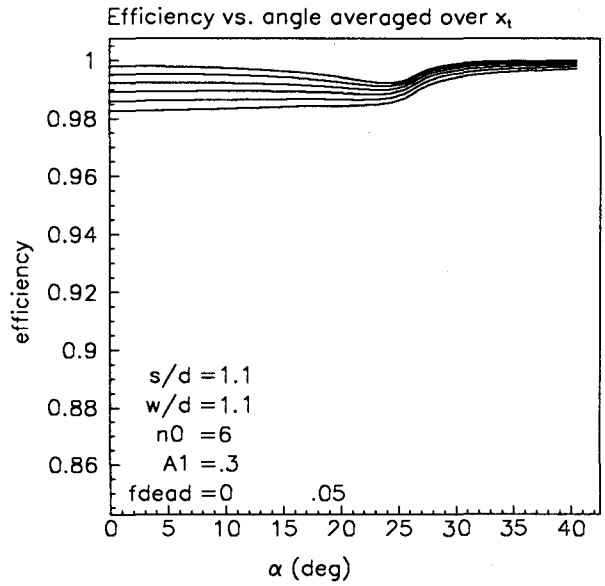

Figure 9. Two-layer efficiency as function of the angle of incidence. The different curves are different values of the fraction of dead channels. The values are f_{dead} = 0.00, 0.01, 0.02, 0.03, 0.04 and 0.05 from top to bottom. The other parameters are fixed at their default values. The default value f_{dead} = 0.01 is the second curve from the top.

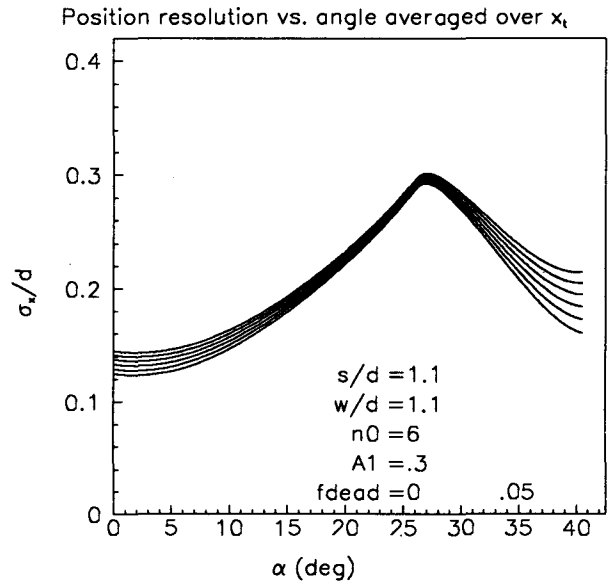

Figure 10. Position resolution as function of the angle of incidence. The different curves are different values of the fraction of dead channels. The values are f_{dead} = 0.00, 0.01, 0.02, 0.03, 0.04 and 0.05 from bottom. to top. The other parameters are fixed at their default values. The default value f_{dead} = 0.01 is the second curve from the bottom.

role if the photon counts are decreased. It is also important to remember that the expected photon count that we have used is the minimum expected, i.e. that from $\eta = 0$. The count will be significantly higher for much of the fiber length ensuring even better performance.

Our choice of fiber spacing $s/d = 1.1$ is appropriate if we demand the efficiency remain high for all incident angles. Figure 1 shows that the efficiency drops rapidly above 15 degrees incident angle if the spacing is increased. As expected, the best efficiency is obtained by packing the fibers as closely together as possible, i.e. by minimizing both the fiber and layer spacings. It is interesting to note that the best resolution is obtained with $s/d = 1.1$ or 1.2 rather than 1.0 because the absence of a signal in one layer provides the information that the track passed through a gap in that layer.

Acknowledgments

This work was supported by the TNRLC and DOE. Thanks to M. Corcoran for reviewing this manuscript.

References

1. Solenoidal Detector Collaboration, "SDC Technical Design Report," **SDC-91-201** (April 1992).
2. Fiber Tracking Group, "Conceptual Design Scintillating Fiber Outer Tracker," **SDC-91-174** (January 1992).
3. D0 Collaboration, "E823 (D0 Upgrade) Step 1 and Beyond," **D0 note 1426** (May 1992).