BABAR Note # **474**
November 24, 1998

BABAR Barrel Calorimeter Crystal Positions

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Abstract

The actual positions of the BABAR barrel crystals were calculated from measurements taken during module assembly and module alignment. The numbers and calculations are described in this note.

1 Introduction

The position of the crystals in the calorimeter has to be known as good as possible. Especially the angular position with respect to the interaction point should be known to fractions of a millimeter. The calculations for the actual location of the barrel crystals are described in this note. The coordinates involved are:

- z as defined in the BABAR coordinate system with $z = 0$ at the interaction point and $z > 0$ for the forward half of the detector.
- r as the radial distance from the beam line. r is perpendicular to z.
- The angle ϕ as defined in the BABAR coordinate system with $\phi = 0^\circ$ pointing out of the ring and $\phi = 90^\circ$ pointing up.
- The angle θ as the angle with the z-coordinate. As usual, the angle $\theta = 0^\circ$ corresponds to far forward, while $\theta = 180^\circ$ corresponds to far backward.

The input for the calculations are:

- The nominal crystal dimensions of Tables 3 and 4 in Appendix A.
- The nominal crystal positions in r and z from Tables 5 and 6 in Appendix B.
- The drawing of the module cross section in the r-ϕ plane (Figure 3).
- From the Oracle data base the following information for each crystal: The crystal's serial number ("BCAL" number), its position in the module (e.g., row 10 center), the serial number of the module ("MB-" number), the offset of the front edge of the carbon fiber structure with respect to the assembly trough, and the distance along the carbon fiber wall from the front edge of the carbon fiber housing to the crystal.
- The positions of the modules inside the cylinder.
- Measurements of the size of the gaps between the modules after alignment.

For simplicity, we will list most numbers with precisions to 0.001 mm, even though several input numbers are not known to this precision. A comment about the notation: If we deal with a number which is still not yet the final crystal coordinate, we will attach the subscript "0".

2 Crystal Shape

As a reminder, Figure 1 provides a drawing of the typical crystal shape with perspective view, top view, and side view. The small end (with dimensions A, B, & C) is at the inner side of the calorimeter. The photodiodes and pre-amplifiers are mounted at other end. Dimensions A to F and the length are given in Appendix A for the 48 crystal types of the barrel.

Note that the front face (with dimensions A, B, C) is parallel to the rear face (with dimensions D, E, F), and that the connecting line between the centers of the two faces is perpendicular to the two faces.

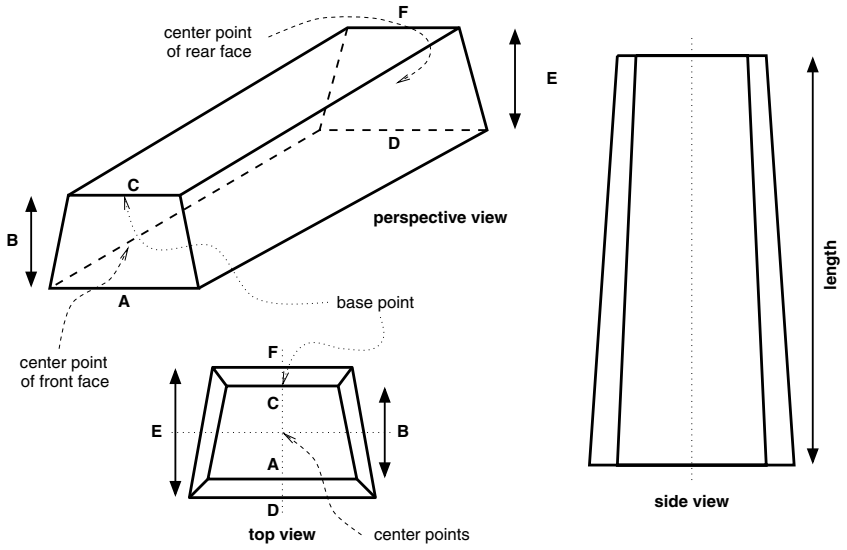

Figure 1: Trapezoidal shape of the crystals. Not to scale. Note that the front and rear faces are parallel to each other and that their center points are lined up perpendicular to their plane. The calculations first focus on obtaining the position of the point labeled "base point". Once its position is known, all other points of the crystal can be calculated.

The calculations first concentrate on the point on the front face along the edge far from the interaction point (IP), and in the center with respect to ϕ. Let us call this point the base point and note it with a star (*) (see Figure 1). Later we will also obtain the coordinates of the center point C_f of the front face and the center point C_r of the rear face of the crystal (again see Figure 1).

3 The Nominal Crystal Positions

The nominal r- and z-positions of the crystals are shown in Figure 2 and listed in Tables 5 and 6 of Appendix B. These r- and z-coordinates do not belong to any corner of crystals, but to the middle of the center crystal, marked in Figure 3 with the letters R and S. Note that this is the point right in between the two corners points S' and S" which have the same z, but a slightly larger value for the r-coordinate than the center point.

Additional information is obtained from a drawing in the r-ϕ plane (Figure 3). It shows three crystals located inside the carbon fiber housing. The most important numbers to note are (1) the size of the gap between two adjacent carbon fiber housings (0.030 inches = 0.762 mm), (2) the thickness of the Tyvek, aluminum foil, and Mylar layers around the crystals (0.0138 inches = 0.350 mm), and (3) the distance of the edge of the carbon fiber housings to the interaction point (917 mm from P to IP). Also note that the walls of the carbon fiber housings focus not at the interaction point, but at point Q at the distance $\Delta r = 0.2934$ inches = 7.453 mm from the interaction point.

The nominal ϕ-position of the center crystals is very easy. The modules are arranged in 40 rows with the gap between row 1 and row 40 at angle $\phi = 0°$, row 1 at $\phi > 0°$ and so on. For the

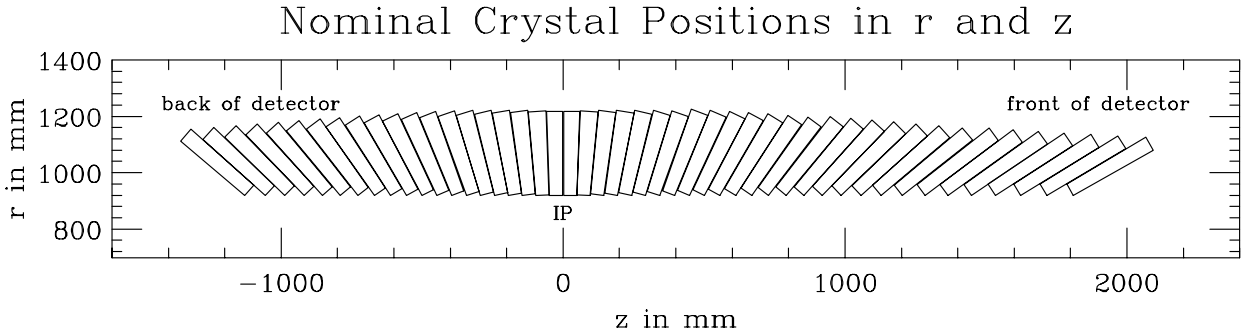

Figure 2: Nominal positions of barrel crystal in r- and z-coordinates.

modules located in row n of the cylinder, the symmetry axis of the center crystal is then at:

$$\phi = (9n - 4.5)^\circ \tag{1}$$

For example, crystal BCAL 4084 (Type B6-20) is the center crystal of ring 20 in module MB6-03. Module MB6-03 sits in cylinder row 31, and therefore the ϕ of the center of crystal BCAL 4084 is $\phi_* = 274.5^\circ$.

We now have the (nominal) r- and ϕ-coordinates for a crystal in the center row of a module. Let us now use them to calculate the r- and ϕ-coordinates of the neighboring crystals, of the p- and n-crystals. To facilitate the explanation, please refer to Figure 4.

Let r_0 here be the distance between the interaction point and the base point of the center crystal, while r shall be the distance from IP to the base point T of the neighboring crystal. Remember that Δr is the distance from IP to Q. The length x is then determined as $x = (r_0 - \Delta r)\sin 3^\circ$, while the length y is $y = (r_0 - \Delta r)\cos 3^\circ$. With Pythagoras, we find $r = \sqrt{x^2 + (y + \Delta r)^2}$ or:

$$r = \sqrt{[(r_0 - \Delta r)\sin 3^\circ]^2 + [(r_0 - \Delta r)\cos 3^\circ + \Delta r]^2} \tag{2}$$

The ϕ-angle between the points S, IP, and T is then:

$$\Delta\phi = \arcsin\left(\frac{x}{r}\right) \tag{3}$$

These formulas will again be useful later for the calculations to obtain the r- and ϕ-positions of the actual crystals.

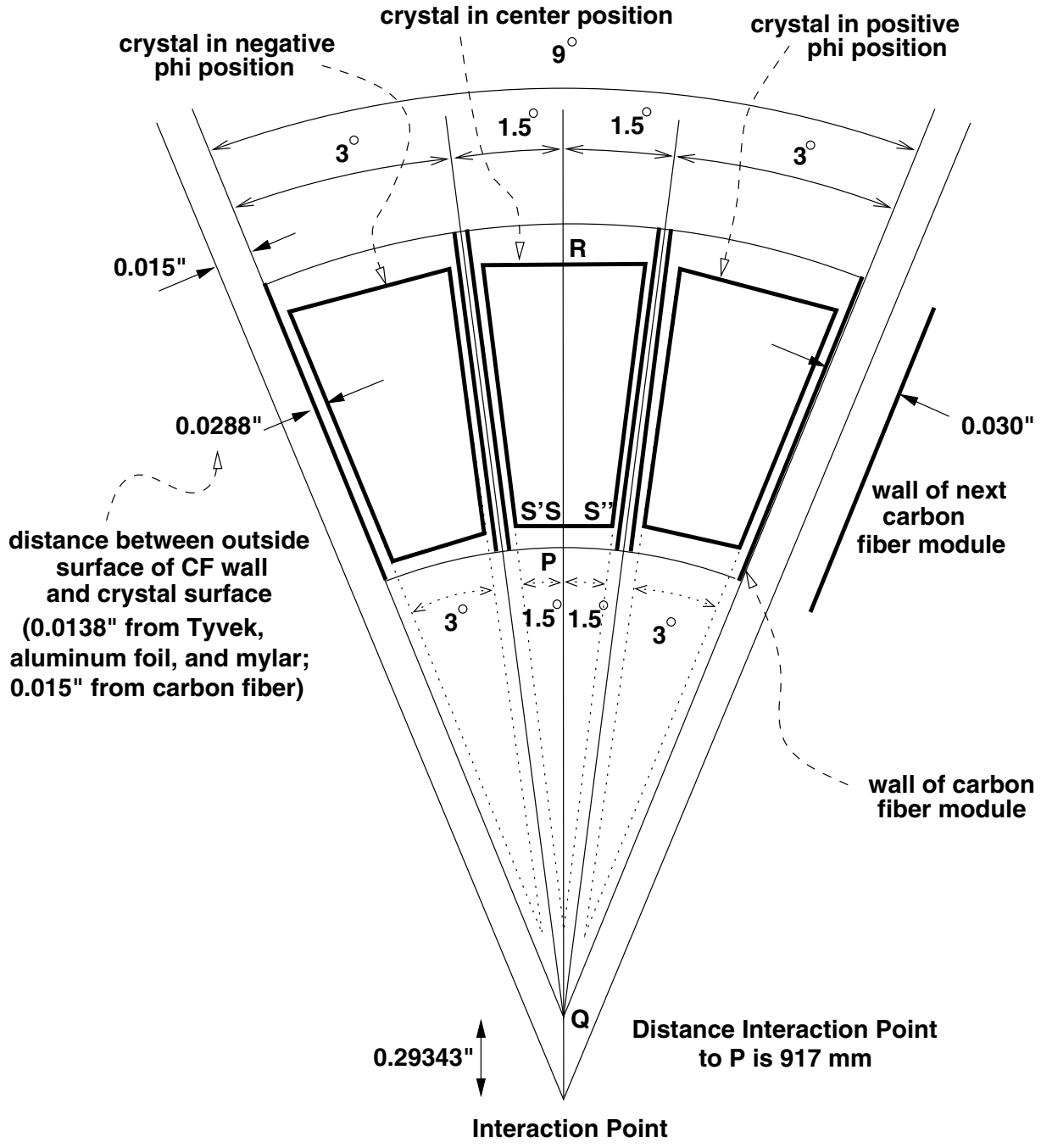

Figure 3: Nominal positions of barrel crystal inside one module shown in r- and ϕ-coordinates. If looking downstream along the $+z$ direction, the left crystal is the n-crystal (at smaller ϕ-position with respect to the center crystal), while the right crystal is the p-crystal.

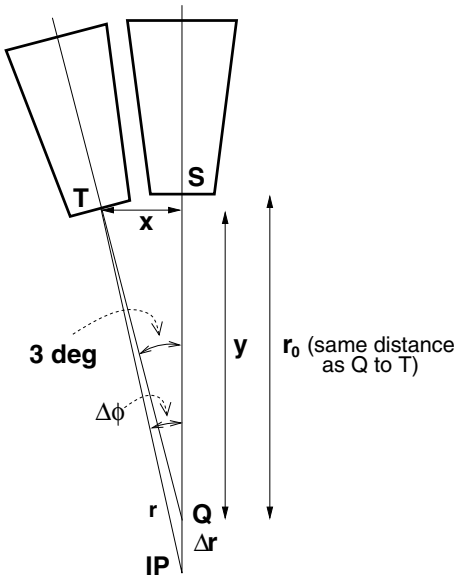

Figure 4: Sketch for the calculation of r and ϕ of p- and n-crystals. Points S and T are assumed to be at the same distance from point Q. For the nominal position, this is true at all times. For the calculation involving actual crystals, imagine that the crystal is first in the center position (labeled with point S) and later rotated by 3° around point Q into the p- or n-position.

4 The Correction for the Depth of Crystals inside Modules ("Radial" Distance)

First let us state that we need to know the angle of the carbon fiber wall along the far side of the crystals (Figure 5). We call this angle θ, and we can obtain it easily from the nominal crystal positions of Tables 5 and 6.

Inside each module, the crystals are actually not sitting at the nominal crystal position. During module assembly, each crystal was pushed down as far as possible, with tape wrapped around the crystal to act as shim in the case that the crystal was sitting too low. After the crystal was fixed in place with epoxy, the distance of the crystal to the edge of the carbon fiber was measured with a caliper. This measurement was taken at the front and far end (the side farther from the IP in z) of the crystal. Two measurements were done for each crystal, one on the positive ϕ corner, one at the negative ϕ corner. Figure 5 shows the places where these two measurements were taken.

In the lowest part of this figure is an enlargement of the place of the measurement. We see the crystal, the wrapping (Tyvek, aluminum foil, and Mylar), as well as the carbon fiber wall and its front edge. The measurements were taken along the carbon fiber wall from point I to H.[1] However, we need to know the distance from point K to J. Both lines make the same angle θ with the edge of the carbon fiber housing. The distance from point J to J' is equal to the thickness of the wrapping, which is estimated to be at $h_{\mathrm{wrap}} = 0.350\,\mathrm{mm}$. The distance from point J' to K' is equal to the one

[1] During module assembly, these measurements were never supposed to be less than 2 mm. Instead, if they were less, one tried to adjust the depth of the crystals in the modules by wrapping tape around the crystals ("shimming").

from point I to H, which is the "radial" measurement. The distance I to H was measured twice, and we take the average of the two measurements and call it $h_{\rm rm}$. Finally, from point K' to K, the distance is:

$$h_{\rm rmwrap} = \left| \frac{0.350 \text{ mm}}{\tan\theta} \right| \tag{4}$$

Here we again used the thickness 0.350 mm of the wrapping. By taking the absolute value we make sure to have a positive number for $h_{\rm rmwrap}$ even if θ is larger than 90° (for the crystals in the backward half of the cylinder).

Since we are focusing on the position of the center point S, not of the corner points S' or S", $h_{\rm rm}$ is an overestimation. The edge of the carbon fiber is cut to a radius of 917 mm $- \Delta r = 909.547$ mm and is therefore closer to S than to S' and S" by the distance $h_{\rm rad} = 909.547\,\text{mm}\,[1 - \cos 1.5^\circ] = 0.312$ mm.

In addition to the crystals not sliding into their destined position in the carbon fiber housings, also the front edge of the carbon fiber housing was sometimes off with respect to the assembly trough due to inaccurate cut of the carbon fiber. This has to be taken into account since the alignment target and the strongback were both glued onto the carbon fiber housing with the troughs as support and reference. During module assembly, the distance of the bottom carbon fiber edge to four special holes in the assembly trough was recorded. A perfect carbon fiber housing would have results of zero in all four measurements. If the carbon fiber edge was too far forward (too low in the trough), the measurements became negative. The four measurements were done in radial distance. They were averaged for this calculation, and we call the result $h_{\rm mod}$ (see Figure 6).

Now we can calculate:

$$r_{*\,0} = 917 \text{ mm} + h_{\rm mod} + (h_{\rm rm} - h_{\rm rad} + h_{\rm wrap} + h_{\rm rmwrap}) \sin\theta \tag{5}$$

For the center crystals, this is already the corrected radial position of the base point: $r_{*\,\rm c} = r_{*\,0}$.

The radial position for the p- and n-crystals needs in addition the Equation 2 applied. Note that the radial distance of 917 mm for the edge of the carbon fiber is only correct for a crystal in the center position. For the p- and n-crystals, imagine that we first assume them to be in the center position, and that we later move them along the ϕ-direction into their p- and n-position. We therefore may calculate r_0 as in Equation 5, but then plug r_0 into Equation 2 to obtain the final radial positions of the p- and n-crystals $r_{*\,\rm p}$ and $r_{*\,\rm n}$.

The ϕ-coordinate can now also be easily calculated for the p- and n-crystals via Equation 3. No additional corrections are being applied to the r- and ϕ-coordinates.

The z-coordinate is being calculated similarly as the r-coordinate, but has an additional correction from the module alignment which will be discussed in the next section. Fortunately, the formulas for the z-coordinate are independent of ϕ, so the z-coordinate of the base point is the same as of the neighboring corners. No special accommodations have to be made for the p- and n-crystals.

We start with the nominal value $z_{*\,\rm nom}$ as given in Tables 5 and 6. We then imagine shifting the crystal down along the far-side carbon fiber wall from the nominal position to the nominal edge of the carbon fiber (from point 1 to point 2 in Figure 6). This radial distance is:

$$h_{\rm nom} = r_{*\,\rm nom} - 917 \text{ mm} \tag{6}$$

Depending on the module shift $h_{\rm mod}$, the carbon fiber edge is a little higher or lower. Along the far-side carbon fiber wall, this corresponds to the distance $h_{\rm mod}/\sin\theta$ (point 2 to point 3).

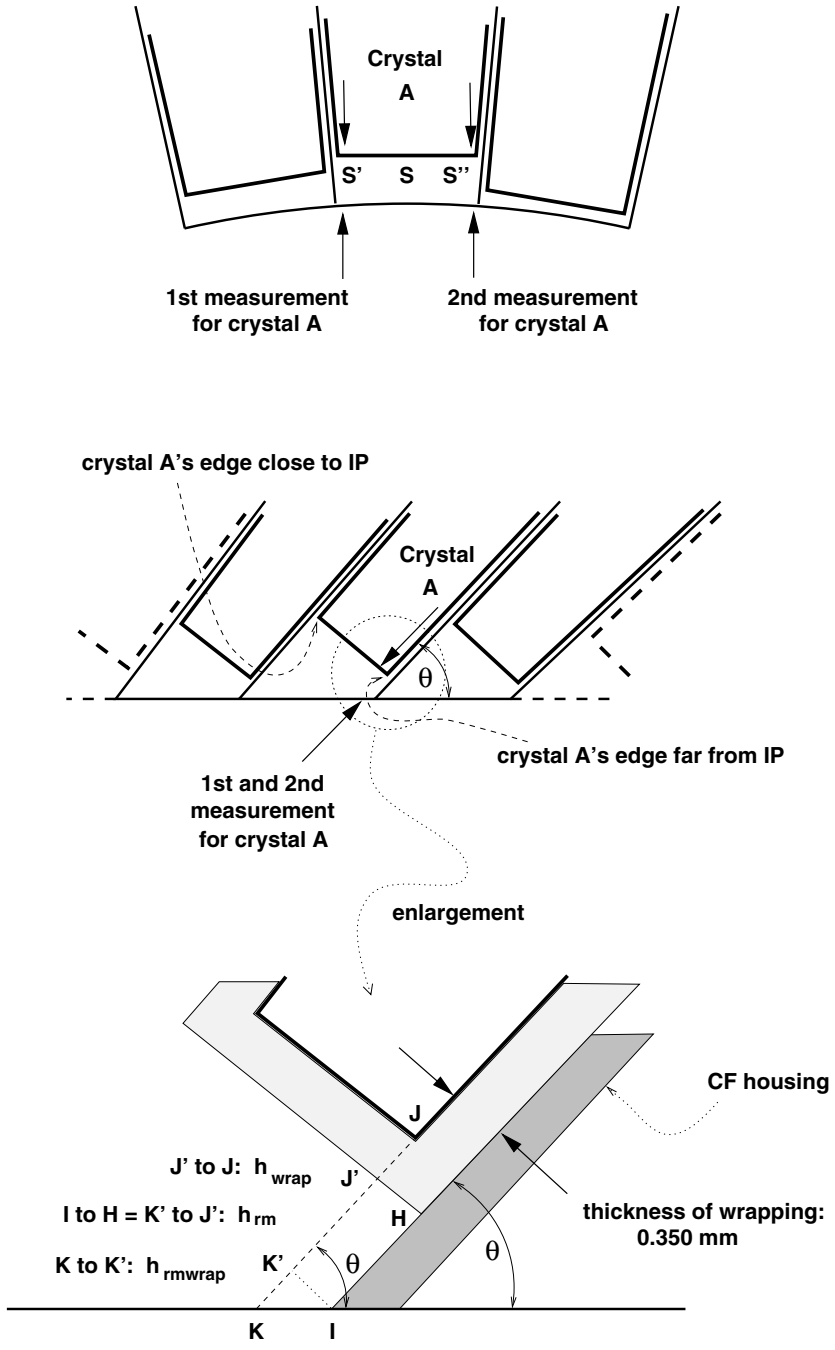

Figure 5: Sketch indicating where the two "radial" measurements were taken for each crystal and how the measurement was influenced by the curvature of the carbon fiber edge and by the crystal wrapping. The caliper was set flush along the wall at the far-end side of the crystal.

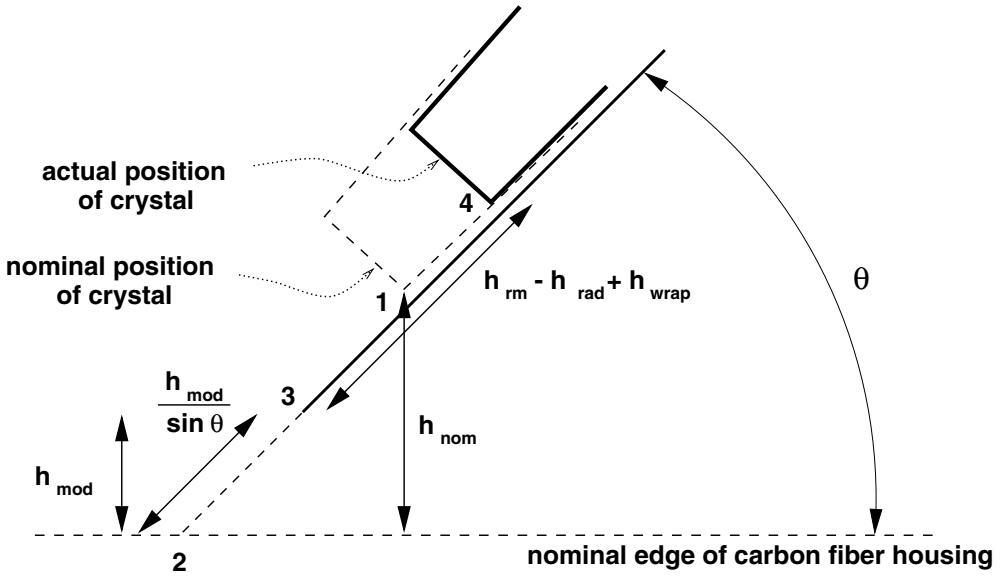

Figure 6: Sketch illustrating the correction to the r- and z-positions of a crystal not sitting at the nominal position in a module.

Now we take into account the "radial" distance $h_{\rm rm}$ measured during module assembly with the additional $h_{\rm wrap} = 0.350\,{\rm mm}$ from the Tyvek/aluminum foil/Mylar wrapping and the additional $h_{\rm rad} = 0.312\,{\rm mm}$ for the overestimation of the "radial" distance due to the curvature of the carbon fiber edge. In Figure 6, this leads us from point 3 to point 4. The formula to obtain the z-coordinate is then:

$$z_{*\,0} = z_{*\,\rm nom} + \left(\frac{h_{\rm mod} - h_{\rm nom}}{\sin\theta} + h_{\rm rm} - h_{\rm rad} + h_{\rm wrap} + h_{\rm rmwrap}\right)\cos\theta \tag{7}$$

The result $z_{*\,0}$ is not yet the final result. The additional z-correction from the module alignment will be discussed in a later section.

Example: In order to illustrate the procedure, we will present here the calculations for the above mentioned crystal BCAL 4084 (type B6-20 in module MB6-03) as well as for crystal BCAL 2825, a type B2-12 crystal located in module MB2-09. For BCAL 4084, the module shift is $h_{\rm mod} = (0{+}0{-}0.5{+}0)\,{\rm mm}/4 = -0.125\,{\rm mm}$ and the "radial" distance is $h_{\rm rm} = (5.98{+}5.91)\,{\rm mm}/2 = 5.945\,{\rm mm}$. From Table 6 we obtain the angle of the far-end plane of a type B6-20 crystal:

$$\theta = \arctan\left(\frac{1123.133 - 919.552}{1370.528 - 1128.529}\right) = 40.072^\circ \tag{8}$$

The value of $h_{\rm rmwrap}$ is $h_{\rm rmwrap} = 0.350\ {\rm mm}/\tan 40.072^\circ = 0.416\ {\rm mm}$. The radial distance r_0 can now be calculated via Equation 5. Since BCAL 4084 is a center crystal, this value is equal to the final radial position:

$$\begin{aligned} r_* = r_{*\,0} = \;& 917\ {\rm mm} - 0.125 \\ & + (5.945\ {\rm mm} - 0.312\ {\rm mm} + 0.350\ {\rm mm} + 0.416\ {\rm mm})\sin 40.072^\circ = 920.994\ {\rm mm} \end{aligned} \tag{9}$$

The angle ϕ of the BCAL 4084 base point was already earlier calculated as 274.5°. The z-coordinate $z_{*\,0}$ of the base point (without correction from module alignment) is calculated as follows: According

to Equation 6, the shift $h_{\rm nom}$ comes out to be $h_{\rm nom} = 919.552$ mm $- 917$ mm $= 2.552$ mm. Using all the numbers calculated above, we obtain for $z_{*\,0}$:

$$\begin{aligned} z_{*\,0} = \;& 1128.529 \text{ mm} + \Big(\frac{-0.125 \text{ mm} - 2.552 \text{ mm}}{\sin 40.072^\circ} + 5.945 \text{ mm} \\ & - 0.312 \text{ mm} + 0.350 \text{ mm} + 0.416 \text{ mm} \Big) \cos 40.072^\circ \\ = \;& 1130.244 \text{ mm} \end{aligned} \tag{10}$$

For crystal BCAL 2825 we have

$$h_{\rm mod} = (0 + 0 + 0.5 + 0.5) \text{ mm}/4 = 0.25 \text{ mm}, \tag{11}$$

$$h_{\rm rm} = (6.52 + 6.56) \text{ mm}/2 = 6.54 \text{ mm}, \tag{12}$$

$$\theta = \arctan\Big(\frac{1169.637 - 919.383}{-773.404 + 612.220}\Big) = 122.785^\circ, \tag{13}$$

$$\text{and} \quad h_{\rm rmwrap} = 0.350 \text{ mm}/\tan 122.785^\circ = 0.225 \text{ mm}. \tag{14}$$

Via Equation 5, we obtain $r_{*\,0} = 922.970\,$mm. Since this crystal is a p-crystal, we have to also use Equation 3. Here $x = (922.970 \text{ mm} - 7.453 \text{ mm}) \sin 3^\circ = 47.914\,$mm, and $y = (922.970 \text{ mm} - 7.453 \text{ mm}) \cos 3^\circ = 914.262\,$mm, so the final radial position of BCAL 2825's base point is $r_* = \sqrt{47.914^2 + (914.262 + 7.453)^2}$ mm $= 922.960\,$mm. To obtain the ϕ-position, we use Equations 1 and 3. Note that module MB2-09 sits in cylinder-row 15:

$$\phi_* = (9 \times 15 - 4.5)^\circ + \arcsin\left(\frac{47.914}{922.960}\right) = 133.476^\circ \tag{15}$$

For the z-coordinate, we have $h_{\rm nom} = 919.383$ mm $- 917$ mm $= 2.383\,$mm. Equation 7 gives us then:

$$\begin{aligned} z_{*\,0} = \;& - 612.220 \text{ mm} + \Big(\frac{0.25 - 2.383 \text{ mm}}{\sin 122.785^\circ} + 6.540 \text{ mm} \\ & - 0.312 \text{ mm} + 0.350 \text{ mm} + 0.225 \text{ mm} \Big) \cos 122.785^\circ \\ = \;& - 614.530 \text{ mm} \end{aligned} \tag{16}$$

5 The Correction from Module Alignment

After the installation of the modules in the cylinder, the modules had to be aligned. For this, the alignment targets were re-attached to the modules, and the modules were moved along the r-direction, along the ϕ-direction, and along the z-direction. Any twist like the $+z$-end of the module being at higher r than the $-z$-end, or the $+z$-end being at larger ϕ than the $-z$-end was also removed. The alignment process continued until each module was at the "perfect" position according to the alignment tools.

For the z-position, no alignment target was available. Instead the MB7 modules (far forward) were pushed in $+z$-direction until they all barely touched a special metal plate which was aligned with the cylinder to a special z-position, so that the forward ends of the MB7 modules were in the design position. The MB6 modules were then aligned so that the gap between the MB6 and MB7 modules was minimal without the modules touching each other. Similarly, the remaining modules were aligned. After the alignment, all gaps between the modules were remeasured by trying to insert Mylar sheets of known thickness in the gap (see Figure 7). The thickness of the Mylar sheets varied in 0.25 mm steps. The thickness of the thickest Mylar sheet still fitting into the gap was then recorded.

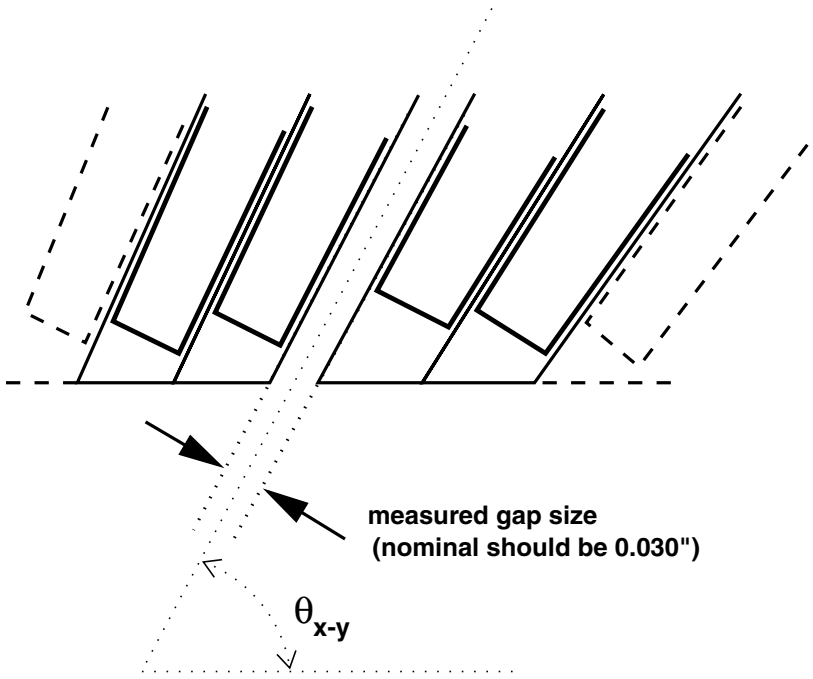

Figure 7: Sketch of the gap between two modules.

Figure 7 is a sketch showing the variables for this correction. To apply the module alignment correction to the z-coordinate, we first need the θ-angle between the modules. From the nominal r- and z-coordinates in Tables 5 and 6, we obtain the following angles:

$$\begin{array}{ll} \text{between MB6 and MB7:} & \theta_{6-7} = \ 38.274^\circ \\ \text{between MB5 and MB6:} & \theta_{5-6} = \ 52.466^\circ \\ \text{between MB4 and MB5:} & \theta_{4-5} = \ 70.332^\circ \\ \text{between MB1 and MB4:} & \theta_{1-4} = \ 90.000^\circ \\ \text{between MB2 and MB1:} & \theta_{2-1} = 109.668^\circ \\ \text{between MB3 and MB2:} & \theta_{3-2} = 127.534^\circ \end{array} \tag{17}$$

The initial z-coordinate of the crystal is $z_{*\,0}$. The nominal distance perpendicular across the gap is $g_{\rm nom} = 0.030\,\text{inches} = 0.762\,\text{mm}$. Let g_{x-y} be the measured gap size between module types Bx and By. Then the shift which we have to apply to $z_{*\,0}$ because of the Bx-By gap is $\Delta z = (g_{\rm nom} - g_{x-y})\sin\theta_{x-y}$. If the actual gap size g_{x-y} is larger than the nominal gap size $g_{\rm nom}$, the shift Δz becomes negative. So we have to <u>add</u> Δz to z_0 for each crystal which is on the backward side of the Bx-By gap.

Example: Let us go back to the two example crystals from above. Crystal BCAL 4084 has a z-position of $z_{*\,0} = 1130.244$ mm without the correction from the module gaps. Since the crystal sits in an MB6 module and is located in cylinder-row 31, we only have to know the module gap between the MB6 and MB7 modules. For row 31 this is $g_{6-7} = 0.25\,\text{mm}$. The shift which we have to apply to $z_{*\,0}$ is then $\Delta z = (0.762 - 0.25)\ \text{mm}\ \sin 38.274^\circ = 0.317\,\text{mm}$. The final z-position of BCAL 4084 is then $z_* = 1130.561\,\text{mm}$.

Crystal BCAL 2825 starts with $z_{*\,0} = -614.408\,\text{mm}$. It sits in an MB2 module located in cylinder-row 15. We need to know all the gaps between the MB2 and MB7 modules of that row. They are are: $g_{6-7} = 0.25\,\text{mm}$, $g_{5-6} = 0.5\,\text{mm}$, $g_{4-5} = 1\,\text{mm}$, $g_{1-4} = 0.75\,\text{mm}$, and $g_{2-1} = 0.75\,\text{mm}$. Due to all these gaps, the shift is:

$$\begin{aligned} \Delta z = \; & (0.762 - 0.25)\ \text{mm}\ \sin 38.274^\circ + (0.762 - 0.5)\ \text{mm}\ \sin 52.466^\circ \\ & + (0.762 - 1)\ \text{mm}\ \sin 70.332^\circ + (0.762 - 0.75)\ \text{mm}\ \sin 90^\circ \\ & + (0.762 - 0.75)\ \text{mm}\ \sin 109.668^\circ \\ = \; & 0.324\ \text{mm} \end{aligned} \tag{18}$$

The final z-position of BCAL 2825's base point is then $z_* = -614.206\,\text{mm}$.

6 The Coordinates of the Center Points of Front and Rear Crystal Faces

Now it is time to introduce the center points C_f and C_r of the front and rear faces. We will call the coordinates r_{Cf}, ϕ_{Cf}, and z_{Cf}, as well as r_{Cr}, ϕ_{Cr}, and z_{Cr}.

First let us obtain the angle θ_c which the two front and rear center points make with the z-axis. From Tables 5 and 6, we can not only calculate the angle of the far-end surface of the crystal (so far called θ), but also the angle of the IP-end surface of the crystal. Their average gives us θ_c.

The front center point C_f is half the dimension B away from the base point. Dimension B is the same for each crystal type (Tables 3 and 4): B = 46.870 mm. This leads to the z-coordinate:

$$z_{\text{Cf}} = \begin{cases} z_* - \dfrac{B}{2}\sin\theta_c & \text{for B4 to B7 crystals} \\ z_* + \dfrac{B}{2}\sin\theta_c & \text{for B1 to B3 crystals} \end{cases} \tag{19}$$

The radial coordinate is similarly calculated. Due to the carbon fiber edge being centered around point Q and not around IP, we have to start not with r_*, but with $r_{*\,0}$:

$$r_{\text{Cf}\,0} = \begin{cases} r_{*\,0} + \dfrac{B}{2}\cos\theta_c & \text{for B4 to B7 crystals} \\ r_{*\,0} - \dfrac{B}{2}\cos\theta_c & \text{for B1 to B3 crystals} \end{cases} \tag{20}$$

The final radial position r_{Cf} can then be obtained via Equation 2. This step again falls away for the center crystals.

And the ϕ-coordinate ϕ_{Cf} is either the same as ϕ_* (for the center crystals) or can be obtained from Equation 3.

To calculate the coordinates of the rear center point C_r, we have to use the length l of the crystal listed in Tables 3 and 4. Again we will have to be careful for the p- and n-crystals.

The z-coordinate equation is the same for any crystal:

$$z_{\text{Cr}} = z_{\text{Cf}} + l\cos\theta_c \tag{21}$$

For the r-coordinate, we have to start with $r_{\text{Cf}\,0}$ instead of r_{Cf}:

$$r_{\text{Cr}\,0} = r_{\text{Cf}\,0} + l\sin\theta_c \tag{22}$$

For p- and n-crystals, we convert the result again via Equation 2. No conversion is necessary for the center crystals.

For the center crystals, $\phi_{\mathrm{Cr}} = \phi_{\mathrm{Cf}}$, but for the other crystals, we again have to employ Equation 3 with $r_{\mathrm{Cr}\,0}$ as input.

Examples: For crystal BCAL 4084, the $\theta_c = 41.009°$. Since it is a center crystal, Equations 2 and 3 are not needed, and the coordinates of $\mathrm{C_f}$ and $\mathrm{C_r}$ are (with $l = 316.2\,\mathrm{mm}$):

$$\begin{array}{llll} z_{\mathrm{Cf}} = & 1115.183\ \mathrm{mm} & z_{\mathrm{Cr}} = & 1353.790\ \mathrm{mm} \\ r_{\mathrm{Cf}} = & 938.678\ \mathrm{mm} & r_{\mathrm{Cr}} = & 1146.161\ \mathrm{mm} \\ \phi_{\mathrm{Cf}} = & 274.5° & \phi_{\mathrm{Cr}} = & 274.5° \end{array} \tag{23}$$

BCAL 2825 is a p-crystal with $\theta_c = 121.542°$. The intermediate coordinates are with $l = 297.6\,\mathrm{mm}$:

$$\begin{array}{llll} z_{\mathrm{Cf}} = & -594.233\ \mathrm{mm} & z_{\mathrm{Cr}} = & -749.915\ \mathrm{mm} \\ r_{\mathrm{Cf}\,0} = & 935.229\ \mathrm{mm} & r_{\mathrm{Cr}\,0} = & 1188.861\ \mathrm{mm} \end{array} \tag{24}$$

This leads us to the final r- and ϕ-coordinates:

$$\begin{array}{llll} r_{\mathrm{Cf}} = & 935.219\ \mathrm{mm} & r_{\mathrm{Cr}} = & 1188.851\ \mathrm{mm} \\ \phi_{\mathrm{Cf}} = & 133.476° & \phi_{\mathrm{Cr}} = & 133.481° \end{array} \tag{25}$$

All final positions of the example crystals are summarized in Table 1.

Crystal	Point	r	ϕ	z
BCAL 4084	base point	920.994 mm	274.5°	1130.561 mm
BCAL 2825	base point	922.960 mm	133.476°	−614.206 mm
BCAL 4084	$\mathrm{C_f}$	938.678 mm	274.5°	1115.183 mm
BCAL 2825	$\mathrm{C_f}$	935.219 mm	133.476°	−594.233 mm
BCAL 4084	$\mathrm{C_r}$	1146.161 mm	274.5°	1353.790 mm
BCAL 2825	$\mathrm{C_r}$	1188.851 mm	133.481°	−749.915 mm

Table 1: Final position of base points and center points of two crystals calculated as examples.

For the analysis program, we give the coordinates in terms of the r-, θ-, and ϕ-positions of the front center point $\mathrm{C_f}$ with respect to the interaction point, as well as the angle θ_c. The angle θ_c is the angle of the connection between the front and rear center points and determines the tilt of the crystal inside the module. The only number which we have to calculate is θ_{Cf}:

$$\tan\theta_{\mathrm{Cf}} = \frac{r_{\mathrm{Cf}}}{z_{\mathrm{Cf}}} \tag{26}$$

Note that we assume ϕ_{Cf} and ϕ_{Cr} to be the same, although they are strictly speaking different for the p- and n-crystals. From the example, however, we see that we may neglect this difference. Table 2 lists the final results for our two example crystals.

Crystal	r_{Cf}	θ_{Cf}	ϕ_{Cf}	θ_c
BCAL 4084	938.678 mm	40.088°	274.5°	41.009°
BCAL 2825	935.219 mm	122.432°	133.476°	121.542°

Table 2: Final crystal position of the two example crystals given in the coordinates required by the analysis data base.

7 Comments on Errors

The calculations presented here were prepared taking into account all possible known geometrical information. We already mentioned that the r- and ϕ-positions are assumed to be perfect, since the alignment was performed to the best possible positioning of the modules. We also have to assume that the placement of the alignment targets and strongbacks with respect to the carbon fiber housings was done without errors. No additional measurements of their positions is known.

The measurements of the "radial" distances h_{rm} and the measured module shifts h_{mod} were relatively difficult to make. The value of h_{rm} was influenced by the quality of the cut at the front of the carbon fibers, by the thickness of the crystal wrapping, and by the skill and consistency of the measurers. These measurements might be accurate to about 0.2 mm, but might easily be off 0.5 mm or more. The value $h_{\mathrm{wrap}} = 0.350$ mm is similarly not a consistent number and might vary according to the number of layers, the amount of tape used, and the quality of the wrapping. The module shift h_{mod} was "measured" only by estimating where the carbon fiber edge was with respect to a 1-mm-radius hole in the assembly trough. An accuracy of better than 0.25 mm can not be expected. If for some reason the outside wall of the module (where h_{mod} was read off) was shorter than any of the inside walls (along which the "radial" distance h_{rm} was measured), the crystal positions calculations will also be inaccurate.

The method to measure the crystal positions in z by trying to insert sheets of Mylar into the gaps was the most reliable measurement available. However, it still has a few short-comings.

- The results are underestimations of the gap. For example, if a gap size of 0.5 mm was recorded, then the real gap size could be up to 0.75 mm, but not less than 0.5 mm.
- Any single bump along the wall of one module might have decreased the measurement significantly. Possible bumps were, for example, due to epoxy leaking out of the carbon fiber and hardening on the outside. Although the modules were checked for bumps like these, some bumps might not have been noticed or removed completely.
- The measurements of the z-gaps may be systematically off. We can do a cross-check of the quality of the measurements by looking at the measurements of the gaps in ϕ. The ϕ-gap measurements are not being used in the calculations described in this report. In theory, the sum of the ϕ-gaps should be equal to the sum of the nominal gaps, i.e., 40×0.030 inches = 30.5 mm. However, the measurements add up to only 6 mm for the MB7 ring to maximal 17 mm for the MB4 ring. If we assume that the measurements were underestimations by 0 to 0.25 mm, then we could add to each measurement the average underestimation of 0.125 mm. This would add 40×0.125 mm = 5 mm to the sums of the gaps: 11 mm for the MB7 ring,

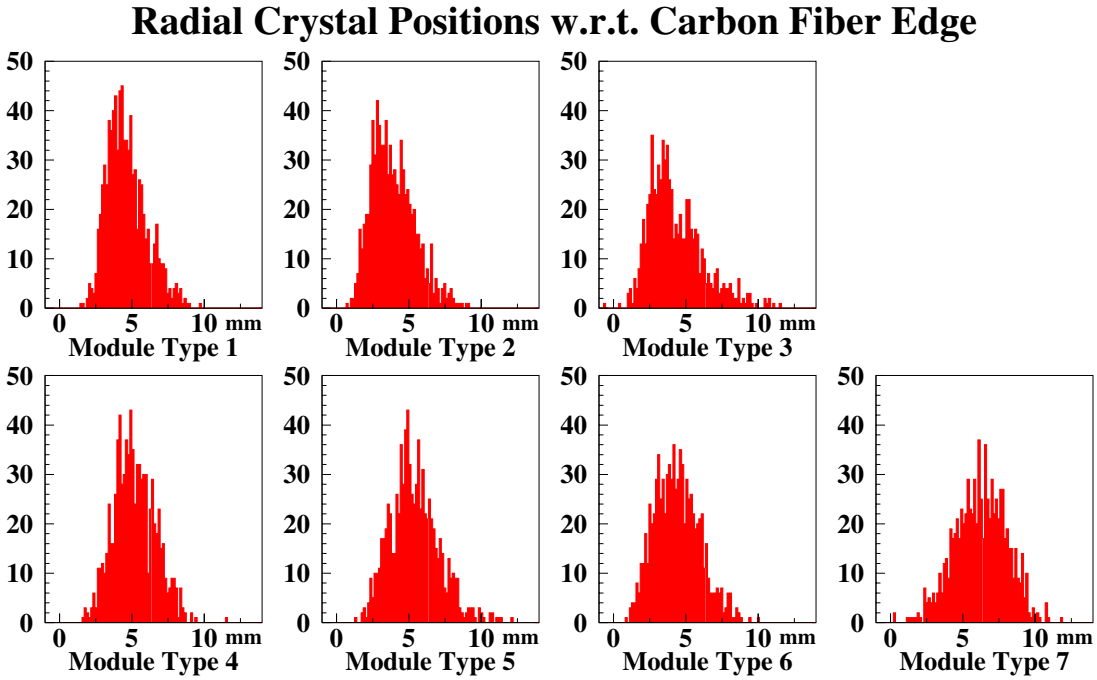

Figure 8: Application of formulas to barrel crystal data: Radial distance from 917 mm radius. The results for the crystals of each module type are shown separately.

22 mm for the MB4 ring. Therefore the gap measurements for the ϕ-coordinate seem to be short by a factor of 1.4 to 2.7, or by a term of (30.5 mm − 22 mm)/40 ≈ 0.2 mm to (30.5 mm − 11 mm)/40 ≈ 0.50 mm. The measurements of the z-gaps may be off by similar factors or terms. Let us again go to our example crystal BCAL 2825. The value of Δz, which was before calculated as 0.324 mm, does now change to the following

$$\begin{aligned} \Delta z = \; & (0.762 - 2 \times 0.25)\ \text{mm}\ \sin 38.274^\circ + (0.762 - 2 \times 0.5)\ \text{mm}\ \sin 52.466^\circ \\ & + (0.762 - 2 \times 1)\ \text{mm}\ \sin 70.332^\circ + (0.762 - 2 \times 0.75)\ \text{mm}\ \sin 90^\circ \\ & + (0.762 - 2 \times 0.75)\ \text{mm}\ \sin 109.668^\circ \\ = \; & -2.625\ \text{mm} \end{aligned} \tag{27}$$

So this additional factor would shift the crystal by about 3 mm in the negative z-direction.

8 Results

The formulas described in this note were applied to the data of the barrel crystals, and the actual crystal positions were calculated. Figure 8 shows the distribution of the radial distance of the base point to the 917 mm radius for all 5760 crystals. For crystals BCAL 4084 and BCAL 2825, these numbers turned out to be 3.994 mm and 5.960 mm. The base point was chosen since it is the point on the crystal closest to the IP.

Separate plots for each crystal type are given in Figure 8. Slight differences in the mean of the plots are, for example, due to the fact that the crystal size of some vendors were in the average

slightly larger or smaller than of other vendors. The plots show that the majority of crystals were within 2 to 10 mm of the 917 mm radius. One crystal (BCAL 3799) turned out to be inside the 917 mm radius by half a millimeter, but this posed no challenge when the radiation shield was inserted at the inside of the modules.

9 Acknowledgments

The data used in the calculation of the crystal positions were collected by many people. The positions of the crystals in the modules and the positions of the modules in the assembly troughs were measured by the module assembly crew which was first lead by Achim Stahl, later by Johannes Bauer. The measurements of the gaps between the modules after alignment came from Giuliana Manzin. All of them are thanked for their careful work. We also thank Eric Doyle for providing us with the drawings and tables of the nominal crystal positions and crystal sizes. And finally we are grateful to Giuliana Manzin and all others who have proofread the note.

A Appendix: Nominal Crystal Dimensions

Ring	A	B	C	D	E	F	Length	Volume
B1-01	4.632	4.687	4.628	6.191	5.823	6.185	29.76	852.4
B1-02	4.644	4.687	4.628	6.202	6.243	6.181	29.76	888.9
B1-03	4.657	4.687	4.628	6.209	6.231	6.171	29.76	888.3
B1-04	4.669	4.687	4.628	6.213	6.215	6.158	29.76	887.1
B1-05	4.682	4.687	4.628	6.212	6.196	6.141	29.76	885.1
B1-06	4.694	4.687	4.629	6.207	6.172	6.121	29.76	882.5
B1-07	4.706	4.687	4.629	6.198	6.146	6.097	29.76	879.4
B2-08	4.717	4.687	4.629	6.185	6.117	6.070	29.76	875.7
B2-09	4.728	4.687	4.629	6.169	6.085	6.041	29.76	871.5
B2-10	4.739	4.687	4.629	6.150	6.052	6.009	29.76	866.9
B2-11	4.749	4.687	4.629	6.128	6.016	5.976	29.76	861.9
B2-12	4.758	4.687	4.630	6.104	5.978	5.940	29.76	856.6
B2-13	4.767	4.687	4.630	6.078	5.940	5.904	29.76	851.1
B2-14	4.775	4.687	4.630	6.049	5.901	5.866	29.76	845.4
B3-15	4.783	4.687	4.630	6.020	5.861	5.828	29.76	839.6
B3-16	4.791	4.687	4.630	5.989	5.820	5.789	29.76	833.7
B3-17	4.798	4.687	4.630	5.957	5.780	5.750	29.76	827.7
B3-18	4.804	4.687	4.630	5.924	5.739	5.711	29.76	821.7
B3-19	4.810	4.687	4.630	5.891	5.699	5.672	29.76	815.8
B3-20	4.816	4.687	4.631	5.858	5.660	5.634	29.76	809.9

Table 3: Nominal dimensions of the backward end barrel crystals. All numbers are given in cm or cm^3. During crystal production, the tolerances on A to F were $\pm$ 0.015 cm and on the length $\pm$ 0.025 cm. For definition of dimensions see Figure 1.

Ring	A	B	C	D	E	F	Length	Volume
B4-01	4.632	4.687	4.628	6.191	5.823	6.185	29.76	852.4
B4-02	4.644	4.687	4.628	6.202	6.243	6.181	29.76	888.9
B4-03	4.657	4.687	4.628	6.209	6.231	6.171	29.76	888.3
B4-04	4.669	4.687	4.628	6.213	6.215	6.158	29.76	887.1
B4-05	4.682	4.687	4.628	6.212	6.196	6.141	29.76	885.1
B4-06	4.694	4.687	4.629	6.207	6.172	6.121	29.76	882.5
B4-07	4.706	4.687	4.629	6.198	6.146	6.097	29.76	879.4
B5-08	4.717	4.687	4.629	6.231	6.162	6.115	30.69	910.9
B5-09	4.728	4.687	4.629	6.214	6.129	6.085	30.69	906.4
B5-10	4.739	4.687	4.629	6.194	6.094	6.052	30.69	901.5
B5-11	4.749	4.687	4.629	6.171	6.057	6.018	30.69	896.2
B5-12	4.758	4.687	4.630	6.146	6.019	5.981	30.69	890.5
B5-13	4.767	4.687	4.630	6.119	5.979	5.943	30.69	884.6
B5-14	4.775	4.687	4.630	6.089	5.939	5.905	30.69	878.5
B6-15	4.783	4.687	4.630	6.097	5.934	5.903	31.62	905.3
B6-16	4.791	4.687	4.630	6.063	5.891	5.861	31.62	898.5
B6-17	4.798	4.687	4.630	6.029	5.848	5.820	31.62	891.6
B6-18	4.804	4.687	4.630	5.994	5.805	5.779	31.62	884.8
B6-19	4.810	4.687	4.630	5.959	5.763	5.737	31.62	878.0
B6-20	4.816	4.687	4.631	5.923	5.721	5.697	31.62	871.3
B6-21	4.821	4.687	4.631	5.887	5.679	5.656	31.62	864.6
B7-22	4.825	4.687	4.631	5.881	5.529	5.652	32.55	876.4
B7-23	4.829	4.687	4.631	5.850	5.483	5.618	32.55	869.6
B7-24	4.833	4.687	4.631	5.820	5.438	5.586	32.55	863.1
B7-25	4.836	4.687	4.631	5.791	5.394	5.555	32.55	856.8
B7-26	4.838	4.687	4.631	5.763	5.352	5.525	32.55	850.8
B7-27	4.841	4.687	4.631	5.736	5.311	5.497	32.55	845.0
B7-28	4.843	4.687	4.631	5.710	5.272	5.471	32.55	839.5

Table 4: Nominal dimensions like in Table 3, but for the forward end barrel crystals.

B Appendix: Nominal Crystal Positions in r- and z-Coordinates

Ring	front/IP		front/far		rear/far		rear/IP	
	z	r	z	r	z	r	z	r
B1-01	−1.315	919.908	−48.175	919.014	−59.533	1216.451	−1.315	1217.562
B1-02	−49.755	922.058	−96.527	919.047	−123.413	1215.532	−61.115	1219.543
B1-03	−98.492	924.527	−145.044	919.085	−187.266	1213.776	−125.379	1221.010
B1-04	−147.65	926.958	−193.859	919.122	−251.148	1211.256	−189.872	1221.646
B1-05	−197.354	929.341	−243.103	919.159	−315.119	1208.012	−254.643	1221.472
B1-06	−247.729	931.664	−292.908	919.195	−379.243	1204.093	−319.743	1220.514
B1-07	−298.898	933.917	−343.406	919.229	−443.599	1199.551	−385.233	1218.812
B2-08	−352.228	936.093	−395.970	919.263	−509.510	1194.445	−452.419	1216.411
B2-09	−405.359	938.183	−448.253	919.295	−574.592	1188.837	−518.898	1213.362
B2-10	−459.66	940.184	−501.631	919.325	−640.188	1182.791	−585.997	1209.723
B2-11	−515.256	942.091	−556.241	919.355	−706.418	1176.369	−653.812	1205.552
B2-12	−572.276	943.900	−612.220	919.383	−773.404	1169.637	−722.451	1200.911
B2-13	−630.852	945.611	−669.712	919.409	−841.284	1162.654	−792.034	1195.862
B2-14	−691.120	947.223	−728.861	919.434	−910.205	1155.478	−862.689	1190.465
B3-15	−754.691	948.738	−791.288	919.457	−981.794	1148.165	−936.033	1184.779
B3-16	−818.762	950.156	−854.196	919.479	−1053.269	1140.765	−1009.266	1178.860
B3-17	−884.951	951.479	−919.213	919.499	−1126.274	1133.324	−1084.022	1172.762
B3-18	−953.411	952.712	−986.498	919.518	−1200.988	1125.885	−1160.469	1166.535
B3-19	−1024.298	953.858	−1056.214	919.536	−1277.597	1118.486	−1238.785	1160.223
B3-20	−1097.775	954.919	−1128.529	919.552	−1356.293	1111.158	−1319.155	1153.867

Table 5: Nominal r- and z-coordinates of the backward end barrel crystals. The four corners of the crystal cut are labeled with respect to their relative distance from the IP: front or rear in r-direction, IP or far in z-direction. The z-coordinates listed here coincide with the ones for the corners, but the r-coordinates in this table are not the ones from the corners, but from the point in between two corner points. See also Figure 2.

Ring	front/far		front/IP		rear/IP		rear/far	
	z	r	z	r	z	r	z	r
B4-01	48.175	919.014	1.315	919.908	1.315	1217.562	59.533	1216.451
B4-02	96.527	919.047	49.755	922.058	61.115	1219.543	123.413	1215.532
B4-03	145.044	919.085	98.492	924.527	125.379	1221.010	187.266	1213.776
B4-04	193.859	919.122	147.65	926.958	189.872	1221.646	251.148	1211.256
B4-05	243.103	919.159	197.354	929.341	254.643	1221.472	315.119	1208.012
B4-06	292.908	919.195	247.729	931.664	319.743	1220.514	379.243	1204.093
B4-07	343.406	919.229	298.898	933.917	385.233	1218.812	443.599	1199.551
B5-08	395.970	919.263	352.228	936.093	455.550	1225.171	513.058	1203.044
B5-09	448.253	919.295	405.359	938.183	522.446	1221.962	578.540	1197.260
B5-10	501.631	919.325	459.66	940.184	589.945	1218.146	644.518	1191.024
B5-11	556.241	919.355	515.256	942.091	658.142	1213.785	711.111	1184.401
B5-12	612.220	919.383	572.276	943.900	727.144	1208.943	778.440	1177.457
B5-13	669.712	919.409	630.852	945.611	797.071	1203.682	846.646	1170.255
B5-14	728.861	919.434	691.120	947.223	868.051	1198.066	915.872	1162.854
B6-15	791.288	919.457	754.691	948.738	947.366	1199.531	993.701	1162.459
B6-16	854.196	919.479	818.762	950.156	1021.172	1193.154	1065.711	1154.595
B6-17	919.213	919.499	884.951	951.479	1096.464	1186.593	1139.215	1146.688
B6-18	986.498	919.518	953.411	952.712	1173.410	1179.899	1214.394	1138.783
B6-19	1056.214	919.536	1024.298	953.858	1252.191	1173.120	1291.433	1130.920
B6-20	1128.529	919.552	1097.775	954.919	1332.991	1166.301	1370.528	1123.133
B6-21	1203.614	919.567	1174.009	955.901	1416.005	1159.480	1451.879	1115.453
B7-22	1283.535	919.580	1254.981	956.747	1510.538	1158.386	1544.222	1114.541
B7-23	1364.241	919.591	1336.632	957.464	1597.317	1152.424	1629.616	1108.117
B7-24	1447.702	919.601	1421.001	958.120	1686.374	1146.644	1717.354	1101.951
B7-25	1533.988	919.610	1508.156	958.718	1777.807	1141.066	1807.538	1096.054
B7-26	1623.160	919.619	1598.159	959.262	1871.708	1135.705	1900.258	1090.434
B7-27	1715.271	919.626	1691.06	959.757	1968.156	1130.571	1995.593	1085.093
B7-28	1810.357	919.633	1786.896	960.207	2067.217	1125.673	2093.607	1080.033

Table 6: Nominal r- and z-coordinates of the forward end barrel crystals. See Table 5 for explanation.