Accuracy Measurements of the Straw Tube Endplates

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May 28, 2003

Introduction

During 2002, full-scale prototype end plate sectors were built at Carnegie Mellon University. This report summarizes findings on the accuracy of the construction of those plates, and procedures for improving their overal accuracy in the final chamber.

Chamber Description

The current construction plan for the CDC calls for building each end plate from 8 pie-shaped sectors that are then mated together to build the complete plates. Each plate has 23 layers of straws. Eight of the layers are aligned at $\pm 6^{\circ}$ stereo tilts with respect to the remaining 15 straight layers. Table 1 gives a description of all of the layers in the chamber. The end plates are machined from the outside of the chamber. The upstream plate from the upstream side and the down stream plate from the down stream side. For the straight through wires, this is not an issue. For the stereo layers, it is crucial that this is treated correctly.

In particular, the stereo wires are closer to the beam line at the center of the chamber than they are at the end plates. The chamber design was optimized to have $0.80cm$ radius (OD) tubes to be radially as close to the adjacent layers as possible, while having an integer number of such tubes in each layer. It also requires that the lips on the plugs at the end of the tubes lie flat against the outside of the end plates. This required that the holes for the stereo wires be drilled at compound angles, and that a shallow flat be machines out for each plug.

Construction Techniques

The downstream set of end plates was constructed first. The straight through holes were drilled with the rotary table clamped directly to the mill's bed, and the outer radius supported with a roller. The center of the rotary table was located and the $x-axis$ of the plate then ran directly from the center out the center of the plate

LAYER	RADIUS[cm]	STRAWS	ϕ_s [∘]	LAYER	RADIUS[cm]	STRAWS	ϕ_s [∘]
1	16.0495	63	0	13	39.2185	154	0
2	17.8313	70	0	14	42.351	161	6
3	19.6133	77	0	15	44.079	168	6
4	21.3954	84	0	16	45.811	175	-6
5	25.490	91	6	17	47.547	182	-6
6	27.121	98	6	18	49.1492	193	0
7	28.769	105	-6	19	50.9317	200	0
8	30.433	112	-6	20	52.7141	207	0
9	32.0890	126	0	21	54.4966	214	0
10	33.8713	133	0	22	56.2791	221	0
11	35.6537	140	0	23	58.0616	228	0
12	37.4361	147	0				

Table 1: Geometrical description of the chamber end plates.

along the mill table. Layouts for all the holes in plate zero are shown in Figure 1. In order to drill the straight through holes, the mill table was advanced along the x axis until the the mill head was at the correct radius from the center. The rotary table was then rotated until the first hole was under the mill head. The table was then told that there were a specific number of holes in the given layer, and that it needed to drill the number of holes that would fit on the plate.

Once these holes were drilled, the rotary table was removed from the mill, and a stack of three sine plates were attached. At the top of this stack, the rotary table was reattached, and then the plates attached. The sine plates were then adjusted to the correct angles for a given stereo layer, and the same procedure as above was used to drill the holes.

The upstream plates had all holes drilled at the top of the stack of sine plates. The original intent was to improve the overall accuracy of the procedure by not mounting and dismounting plates between operations. It was later discovered that the mill bed was tilting slightly during this latter operation. The distortion due to this tilting was measured, and corrections applied.

Measurements

The two sets of end plates were set to Jefferson Lab for measurement. A set of 46 holes, two in each layer, were randomly checked in each plate set. Table 4 gives the results

LY	r [cm]	α [$\circ$]	β [$\circ$]	γ [$\circ$]	LY	r [cm]	α [$\circ$]	β [$\circ$]	γ [$\circ$]
1	16.0495	0	0	0	13	39.2185	0	0	0
2	17.8313	0	0	0	14	42.351	0	1.5078	5.8070
3	19.6133	0	0	0	15	44.079	0	1.4487	5.8219
4	21.3954	0	0	0	16	45.811	5.8369	1.3868	0
5	25.490	0	2.5042	5.4529	17	47.547	5.8487	1.3361	0
6	27.121	0	2.3538	5.5193	18	49.1492	0	0	0
7	28.769	5.5789	2.2086	0	19	50.9317	0	0	0
8	30.433	5.6251	2.0878	0	20	52.7141	0	0	0
9	32.0890	0	0	0	21	54.4966	0	0	0
10	33.8713	0	0	0	22	56.2791	0	0	0
11	35.6537	0	0	0	23	58.0616	0	0	0
12	37.4361	0	0	0					

Table 2: Machining angles for the holes on the upstream end plate. Angles α and γ are rotations about the centerline of the sector. Note that α and γ tilt in the opposite sense. Angle β is a rotation about an axis perpendicular to this. Angle γ corresponds the the sine-plate located closest to the machine bed, while angle α corresponds to that closest to the end plate.

for the down stream plates, while Table 5 gives the results for the upstream plates. In discussions with people at Jefferson lab, the impression is that the measurement accuracy is probably on the order of $0.001\,in$. The measurements were carried out in a room whose temperature was controlled in the $68°F$ to $72°F$ range. It should be noted that the coefficient of thermal expansion for Aluminum is $\alpha_{AL} = 25 \times 10^{-6} (°C)^{-1}$ at $25°C$. Over the $60\,cm$ radius of the chamber, we expect that thermal distortions could be as large as $\pm 0.0017\,cm$, or $0.00067\,in$.

In both the down stream and in the up stream plate, a particular hole (number one) was given a specified set of coordinates. Due to both construction and measurement errors, these holes may not be at the actual specified location. In order to minimize this, the analysis technique started by determining the best location for the center of the plate, and the rotation to Allin the coordinates with this. The results of this minimization are presented in Table 3. Note that in the case of the upstream plate, the angle reported for the first hole as mislabeled, and was about $9.4°$ off. Each hole is transformed according to equation 1, with the variables θ, x_c and y_c being optimized to minimize the deviation from the expected location of each holes. The χ^2 reported in Table 3 are summed only over the non-stereo holes in the plate mentioned.

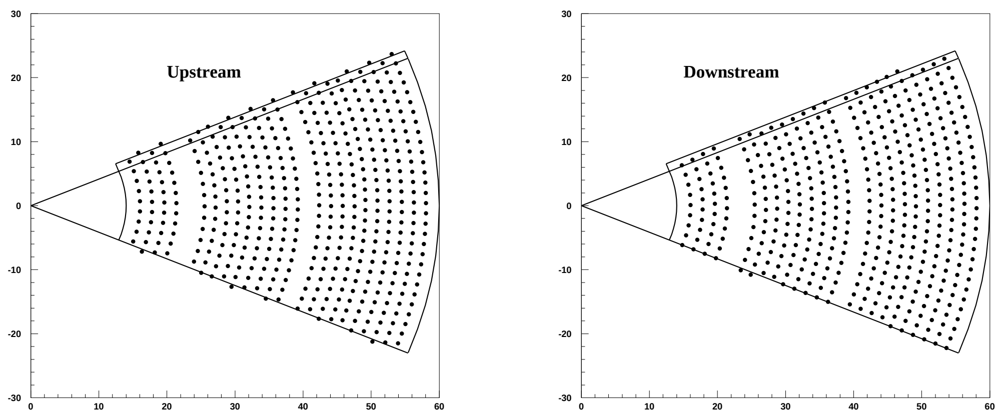

Figure 1: The hole patterns as seen on the outside of plate zero for both the up stream and down stream plates. The machining axes have x and y centered at the center of the wedge and running in the normal directions. x from left to right and y from bottom to top.

$$\begin{pmatrix} x_h \\ y_h \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x - x_c \\ y - y_c \end{pmatrix} \tag{1}$$

The measured location of the stereo hole appears off in the measurements. As far as we can tell, this is wholly associated with the way that the positions of the holes are measured. The measuring machine taps three positions on the sides of the hole walls. From these, it is possible to determine where the center is located. This is done at two different depths, and the average of the two is taken. For the straight through holes, this works fine. However, for the stereo holes, this will return a position that is somewhere near the middle (thickness) of the plate. Because of the stereo angles, this will be shifted away from the position at the surface of the plate. Unfortunately, the depth below the surface of the plates of the two measurements was not recorded during measurement. As such, it is not possible to precisely correct for the location of the stereo holes.

Plate	End	Angle	x_{center}	y_{center}	χ^2_{min}
0	up stream	$9.412°$	$0.006\,cm$	$0.007\,cm$	0.00007
7	up stream	$9.420°$	$0.001\,cm$	$0.010\,cm$	0.00003
0	down stream	$-1.370°$	$0.011\,cm$	$0.015\,cm$	0.00017
7	down stream	$-1.370°$	$0.019\,cm$	$0.002\,cm$	0.00015

Table 3: The deviations from the nominal center of the plate to where the measurement was made.

It was determined after the construction of the upstream plates that the milling machine bed was tilting slightly as the plates were moved back and forth along the plate. The tilting was measured by placing an accurate scale on the mill bed, and then comparing the positions of the mill head and the electronic readout for the head. These problems did not appear to affect the downstream plate as there was less material on the mill bed. The measured corrections for the up stream plates are given in Table 6. Figure 2 shows measurements of Δr versus r for both the up stream and the down stream set of plates. The top row are the direct measurements of the plates compared with the expected positions. The two clusters of data that lie below the rest correspond to the stereo wires in the chamber. The slope of the remaining points is largely due to the mill corrections. After the corrections in Table 6 have been applied, the results are shown in the middle row. The agreement is now significantly better, but there is still a small slope to the Δr versus r plot. We believe that this is due to temperature differences between the rooms in which the plates were machined, and where they were measured. If the slope of the line is fit, and a final correction is applied, then the data shown in the bottom row of Figure 2 is obtained. The same thermal correction is applied to both the upstream and the down stream plates, as no data at the level of $0.5°C$ are available.

Upstream Plates

NO	LY	RW	PL	x [in]	y [in]	NO	LY	RW	PL	x [in]	y [in]
1	1	3	7	-0.00003	0.00005	2	1	13	0	-3.71599	4.77206
3	2	6	7	0.22454	1.72437	4	2	18	0	-5.59797	5.96909
5	3	1	7	1.48525	-0.81869	6	3	10	0	-0.64588	4.30418
7	4	6	7	1.56439	2.15743	8	4	18	0	-3.86309	7.06038
9	5	8	7	2.71515	3.50619	10	5	17	0	-1.60070	7.87485
11	6	2	7	4.43236	-0.62849	12	6	25	0	-5.61409	9.63507
13	7	7	7	4.35335	2.99220	14	7	16	0	0.78934	7.85942
15	8	11	7	3.92811	5.31639	16	8	22	0	-1.62264	10.03414
17	9	5	7	6.23151	1.02415	18	9	18	0	2.46255	8.14074
19	10	9	7	6.13269	3.96376	20	10	26	0	-1.23994	11.34235
21	11	16	7	4.75429	7.71051	22	11	23	0	1.51367	10.68223
23	12	7	7	8.05229	2.59897	24	12	18	7	4.86012	8.67958
25	13	2	7	9.20090	-0.60996	26	13	33	0	-1.98674	13.82267
27	14	19	7	6.49308	9.74934	28	14	29	0	1.43017	13.78715
29	15	18	7	7.79253	9.19514	30	15	41	0	-4.83900	16.27721
31	16	15	7	9.65230	7.51683	32	16	40	0	-3.01916	16.72707
33	17	10	7	11.66831	4.45047	34	17	27	0	5.63342	13.45605
35	18	24	7	8.20068	11.86292	36	18	26	0	7.32857	12.77906
37	19	19	7	10.94947	9.31184	38	19	43	0	-0.78922	18.27688
39	20	7	7	14.27372	2.16501	40	20	35	0	4.90025	16.49131
41	21	11	7	14.48869	4.53798	42	21	39	0	3.79029	17.94732
43	22	15	7	14.24461	7.43647	44	22	29	0	9.36131	14.71672
45	23	3	7	16.60257	0.00027	46	23	55	0	-4.12120	21.74059

Table 4: Measurements on the down stream plate made at Jefferson Lab. The columns labeled NO are the hole numbers, 1 to 46. LY corresponds to the layer in the chamber, 1 to 23. The column labeled RW corresponds to the hole number in the particular layer and PL is the plate in which the hole is located, either 0 or 7. x and y are the measured position of the center of the hole in inches relative to essentially hole number one. Even though the coordinates are reported with five decimal points of accuracy, the true accuracy is estimated to be one the order of ± 0.001 inches.

NO	LY	RW	PL	r [in]	ϕ [°]	NO	LY	RW	PL	r [in]	ϕ [°]
1	1	3	0	6.32487	20.13945	2	1	10	7	6.32549	60.14298
3	2	5	0	7.02716	28.70646	4	2	17	7	7.02785	90.42335
5	3	7	0	7.72934	40.39389	6	3	14	7	7.72935	73.12941
7	4	2	0	8.43004	15.84981	8	4	12	7	8.43085	58.71211
9	5	6	0	10.03552	29.72558	10	5	11	0	10.03467	49.47390
11	6	4	0	10.67642	20.27543	12	6	17	7	10.67858	68.01886
13	7	7	0	11.32649	31.58982	14	7	22	7	11.32954	83.01259
15	8	10	0	11.98305	39.56429	16	8	17	7	11.98480	62.05634
17	9	3	0	12.64217	14.41622	18	9	25	7	12.64342	77.28092
19	10	16	0	13.34547	51.70697	20	10	33	7	13.34559	97.72466
21	11	12	0	14.04725	38.98329	22	11	30	7	14.04767	85.27613
23	12	9	0	14.74880	29.92562	24	12	24	7	14.74958	66.66688
25	13	16	0	15.45116	45.06529	26	13	30	7	15.45100	77.79588
27	14	2	0	16.67684	12.99314	28	14	20	0	16.67999	53.26142
29	15	7	0	17.35992	23.28403	30	15	29	7	17.36020	70.41679
31	16	11	0	18.04173	30.83149	32	16	26	7	18.04337	61.69775
33	17	18	0	18.72535	43.62562	34	17	38	7	18.72734	83.19980
35	18	31	7	19.36079	65.61564	36	18	48	7	19.36136	97.32082
37	19	8	0	20.06261	23.81602	38	19	11	0	20.06278	29.21482
39	20	4	0	20.76390	14.41530	40	20	17	0	20.76471	37.02288
41	21	7	0	21.46626	19.08560	42	21	38	7	21.46699	71.24513
43	22	22	0	22.16893	44.64044	44	22	34	7	22.16887	64.19685
45	23	26	0	22.87112	49.67903	46	23	52	7	22.87175	90.73621

Table 5: Measurements on the up stream plate made at Jefferson Lab. The columns labeled NO are the hole numbers, 1 to 46. LY corresponds to the later in the chamber, 1 to 23. The column labeled RW corresponds to the hole number in the particular layer and PL is the plate in which the hole is located, either 0 or 7. r and ϕ are the measured position of the center of the hole in inches relative to roughly the center of the plate. Even though the coordinates are reported with five decimal points of accuracy, the true accuracy is estimated to be one the order of ± 0.001 inches.

mill (in)	readout (in)	mill (in)	readout (in)	mill (in)	readout (in)
1.0000	1.0000	2.0000	1.9995	3.0000	2.998
4.0000	3.9975	5.0000	4.9965	6.0000	5.996
7.0000	6.9944	8.0000	7.995	8.0000	7.995
10.0000	9.9945	11.0000	10.994	11.0000	10.994
13.0000	12.9935	14.0000	13.9935	15.0000	14.993
16.0000	14.993	17.0000	16.993	18.0000	17.993
19.0000	18.993	20.0000	19.993	21.0000	20.993
22.0000	21.9925	23.0000	22.9925	24.0000	23.992
25.0000	24.9915	26.0000	25.9915	27.0000	26.991
28.0000	27.9905	29.0000	28.9905	30.0000	29.990
31.0000	30.9895	32.0000	31.9895		

Table 6: The distance as measured on the mill surface as compared to the digital readout for the mill.

Corr.	Plate	Angle	x_{center}	y_{center}	χ^2_{min}
A	0	9.412°	0.019 cm	0.015 cm	0.00075
B	0	9.420°	0.006 cm	0.007 cm	0.00011
C	0	9.420°	0.006 cm	0.007 cm	0.00007

Table 7: The deviations from the nominal center of the plate to where the measurement was made.

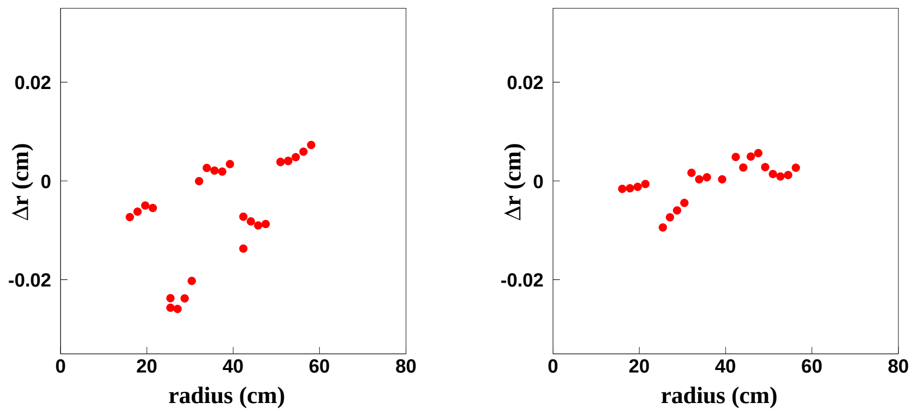

Figure 2: A plot of Δr versus r for the upstream (left column) and downstream (right column) plate zero. The data shown here are bfore any corrections have been made. The data that are consistently low correspond to the stereo layers in the end plates.

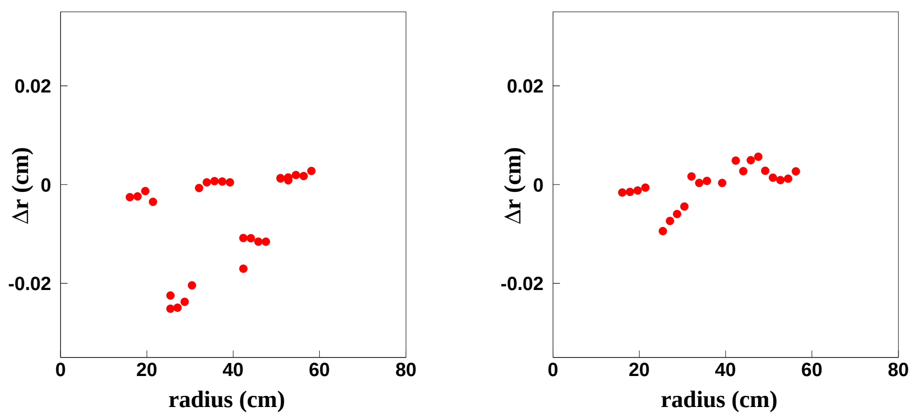

Figure 3: A plot of Δr versus r for the upstream (left column) and downstream (right column) plate zero. These data include corrections for the measured tilt in the mill during manufacture of the upstream plate. The data that are consistently low correspond to the stereo layers in the end plates.

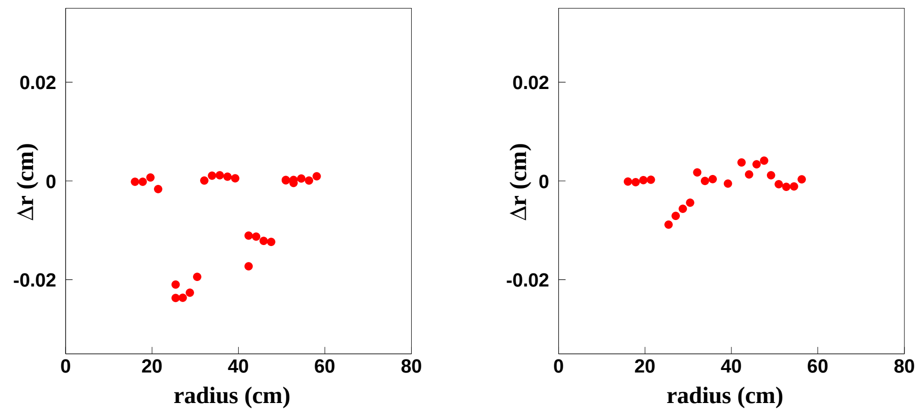

Figure 4: A plot of Δr versus r for the upstream (left column) and downstream (right column) plate zero. These data include both the mill corrections to the upstream plate, and a correction attributed to thermal expansion. The data that are consistently low correspond to the stereo layers in the end plates.

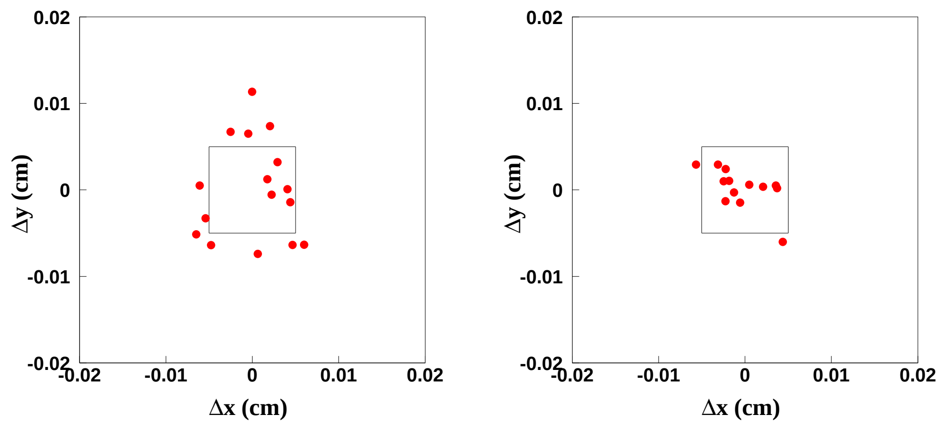

Figure 5: A plot of Δy versus Δx for the upstream (left column) and downstream (right column) plate zero. These data are without any corrections and have excluded the stereo layers.

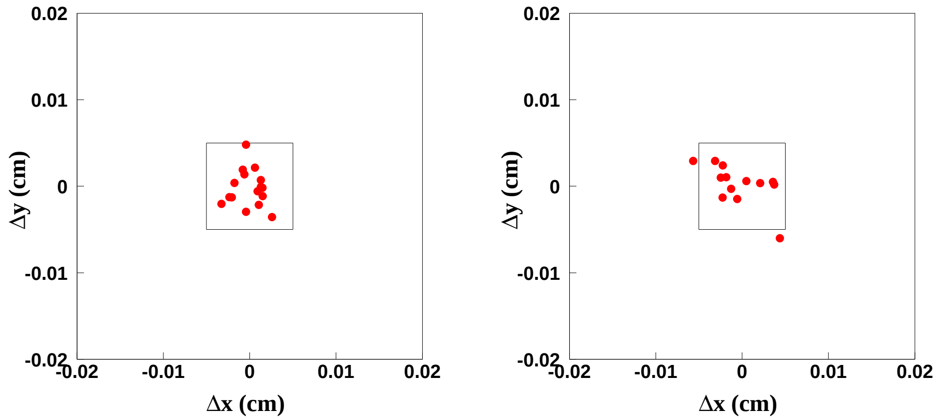

Figure 6: A plot of Δy versus Δx for the upstream (left column) and downstream (right column) plate zero. These data include correction to the upstream plate for the measured tilt in the mill. The stereo layers have been excluded.

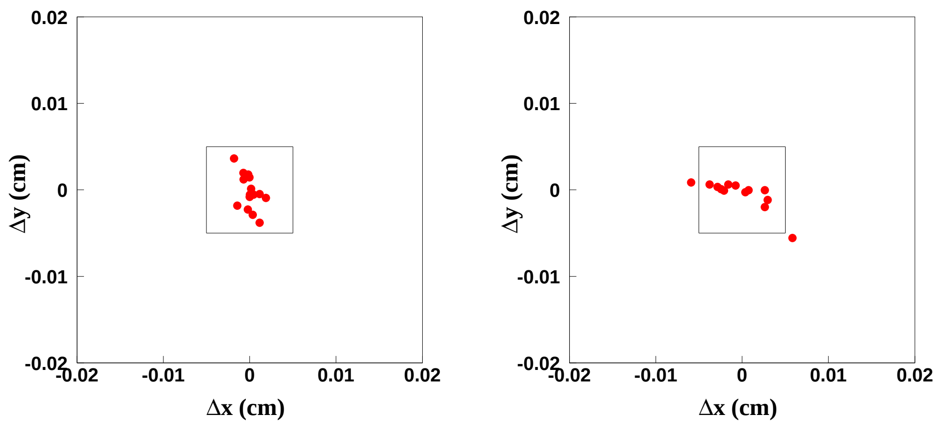

Figure 7: A plot of Δy versus Δx for the upstream (left column) and downstream (right column) plate zero. These data include correction to the upstream plate for the measured tilt in the mill and an estimated correction for thermal expansion. The stereo layers have been excluded.

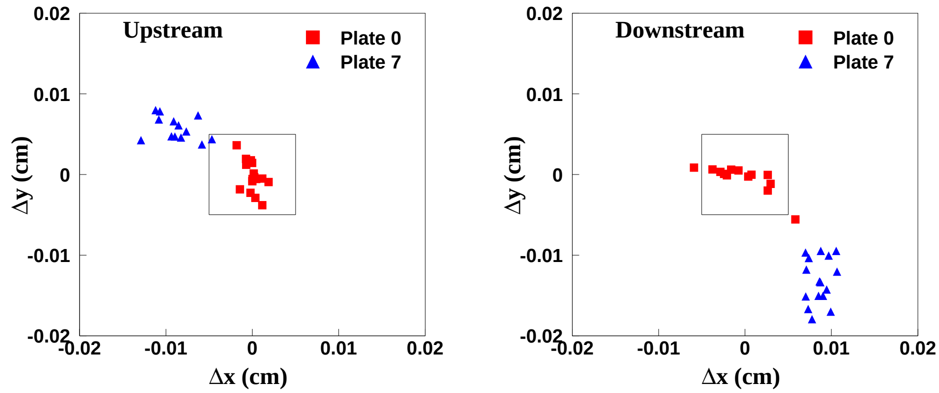

Figure 8: A plot of the deviation in y versus that in x for the upstream and downstream sections. The data have been optimized to plate 0, so all points there are easily withing $\pm 50\mu m$. The data for plate 7 are systematically off indicating that the matching of one plate to the next is not perfect. Note that the upstream plate is significantly better matched than the downstream.

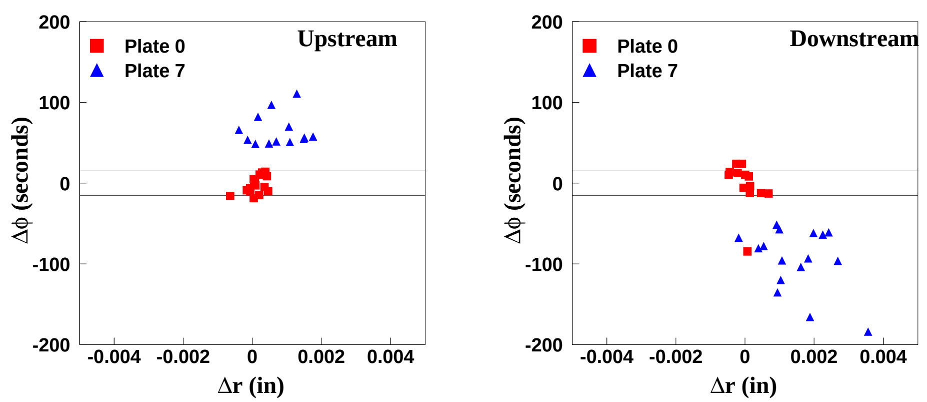

Figure 9: A plot of the deviation in ϕ versus that in r for the upstream and downstream sections. The data have been optimized to plate 0, so all points there are easily withing $\pm 15 sec$ in ϕ and $\pm 0.001\, in$ in r. The data for plate 7 are systematically off indicating that the matching of one plate to the next is not perfect. Note that the upstream plate is significantly better matched than the downstream.