FERMILAB ENGINEERING NOTE	SECTION PPD/ETT	PROJECT BTeV/C0	SERIAL - CATAGORY	PAGE 1
SUBJECT Straightness of Aluminum Tube with 0.008" Wall		NAME Mayling Wong		
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Summary: 6061-T6 aluminum tubes were manufactured so that the wall thickness was nominally 0.008 inch and the inner diameter nominally 1.0 inch. The drawn tube lengths varied from 31 to 120 inches. As a potential BTeV beam pipe, the straightness of the longest tube is adequate for a clear line-of-sight for the beam to pass through if it were supported along its length.

Calculated Sag in Tube

The straightness of the longest tube was measured with its ends simply supported and the maximum deviation from straightness at the center of the tube due to its weight. The tube dimensions are 120 inches long with a 1-inch inner diameter and a wall thickness of 0.008-inch. The tube is made of 6061-T6 aluminum, which has a density of 0.098 lb/in^3 and a modulus of elasticity E = 10x10^6 psi. The tube will sag under its own weight. The distributed weight is calculated, assuming the supports are placed 117 inches apart.

$$w_a = \frac{\gamma * V}{L} = \frac{\lambda * \left(\pi * \left[r_o^{\ 2} - r_i^2\right] * L\right)}{L}$$
$$w_a = \frac{0.098 \frac{lb}{in^3} * \left(\pi * \left[0.504^2 - 0.500^2\right] in^2 * 117\ in\right)}{117} \tag{1}$$
$$w_a = 1.24x10^{-3}\ lb$$

where γ = specific weight = 0.098 lb/in^3
V = tube volume (in^3)
r_o = outer radius = 0.504 in
r_i = inner radius = 0.500 in
L = distance between supports = 117 in

The tube's cross section results in a moment of inertia of:

$$I = \frac{\pi}{4}\left(r_0^4 - r_i^4\right) \tag{2}$$
$$I = 1.59x10^{-3}\ in^4$$

For a tube with these dimensions that is simply supported at its ends, the maximum displacement at the middle of its length is calculated.

$$y_{max} = \frac{5 \; w_a L^4}{384 \; E \; I}$$

$$y_{max} = \frac{5 * 1.24x10^{-3} * 117^4}{384 * 10x10^6 * 1.59x10^{-3}} \qquad (3)$$

$$y_{max} = 0.19 \; \text{in}$$

$$y_{max} = 4.8 \; \text{mm}$$

Measurement Procedure

The straightness of the longest tube was characterized using a coordinate measuring machine at SiDet. Each end of the tube was placed on V-blocks so that the distance between them was 2794.984 mm (117.125 inch). At each V-block and at 5 places along the length of the tube, the roundness, diameter, and center point were recorded. The origin of the coordinate system was designated at the center point of the outer circumference of one end of the tube. The measurements were repeated when the tube was turned 90º, 180º, and 270º from the first position. At each orientation, two sets of measurements were taken. Figure 1 is a photograph of the setup. Figure 2 shows one of the end supports.

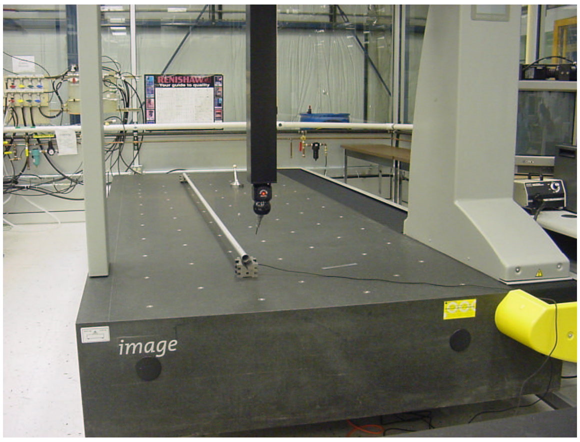

Figure 1 – Tube set up in CMM

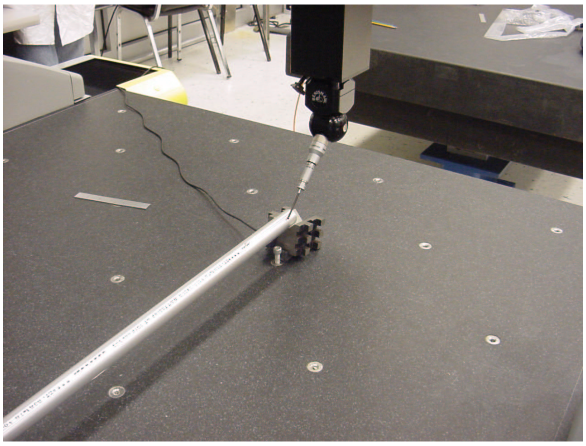

Figure 2 – End support

The tube was then laid flat on the table and the measurements repeated for one orientation. The tube did not rest completely on the table. Rather, the tube sat on the table at two points along its length. To hold the tube in place during measurement taking, double-sided tape was laid between the table and the tube at the contact points. To keep the tube from swaying when touched by the probe, flat pieces of metal were placed on both sides of the tube where the tape was located, as shown in Figure 3. Two sets of measurements were taken.

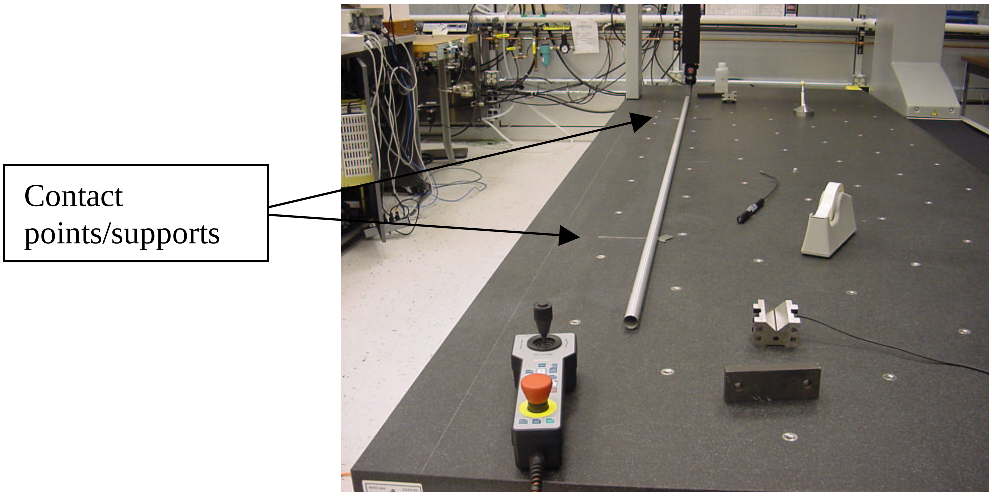

Figure 3 – Supporting the Tube as It Lies Directly on the Table

Results

A set of measurements consisted of establishing the origin of the coordinate system at one end of the tube, then taking measurements at four additional locations along the length of the tube, including the other end of the tube. For each location along the length of the tube, five points on the top half of the tube circumference were measured with the CMM probe. The computer created a best-fit circle through the points to represent the tube's outer diameter at that location. The circle's diameter and centerpoint were recorded. The circle out-of-roundness was also recorded based on the original points. The origin was set at the centerpoint of the circle that was measured at the first end of the tube. The y-axis ran along the axis of the tube parallel to the table. The z-axis pointed up. Tables 1a-d list the average values of the coordinates of the circle centerpoints, the out-of-roundness and the outer diameter for each circle measured by the CMM's computer. Average values are shown because more than one measurement was taken.

Table 1a – Measurements of Tube Oriented at 0º

	Ref Circle 1	Circle 1	Circle 2	Circle 3	Ref Circle 2
Roundness	0.103	0.072	0.055	0.146	0.293
Diameter	25.756	25.745	25.820	25.662	25.992
X	0.000	0.161	0.663	0.222	0.000
Y	0.000	700.000	1400.000	2100.000	2794.984
Z	0.000	-3.454	-4.907	-2.899	0.000

Table 1b – Measurements of Tube Oriented at 90º

	Ref Circle 1	Circle 1	Circle 2	Circle 3	Ref Circle 2
Roundness	0.097	0.034	0.045	0.091	0.127
Diameter	25.634	25.837	25.699	25.965	25.907
X	0.000	-0.898	-1.409	-0.570	0.000
Y	0.000	700.000	1400.000	2100.000	2794.984
Z	0.000	-2.632	-3.922	-2.813	0.000

Table 1c – Measurements of Tube Oriented at 180º

	Ref Circle 1	Circle 1	Circle 2	Circle 3	Ref Circle 2
Roundness	0.067	0.051	0.030	0.045	0.187
Diameter	25.751	25.735	25.866	25.534	25.602
X	0.000	0.346	0.161	0.129	0.000
Y	0.000	700.000	1400.000	2100.000	2794.987
Z	0.000	-1.811	-2.534	-1.055	0.000

Table 1d – Measurements of Tube Oriented at 270º

	Ref Circle 1	Circle 1	Circle 2	Circle 3	Ref Circle 2
Roundness	0.071	0.093	0.053	0.149	0.548
Diameter	25.585	25.792	25.717	25.927	25.688
X	0.000	0.881	1.245	0.451	0.000
Y	0.000	700.000	1400.000	2100.000	2794.984
Z	0.000	-2.717	-3.313	-2.704	0.000

The tube's maximum outer diameter is 25.992 mm for Ref Circle 2 with the tube at 0º. The minimum outer diameter is 25.534 mm for Circle 3 with the tube at 180º. The nominal outer diameter is 25.806 mm.

The tube was characterized according to its maximum deviation from straightness, the deviation of mean diameter, and the clear line-of-sight. In order to define the maximum deviation from straightness, an ideal tube axis is defined as the y-axis of the coordinate system. If the tube were perfectly straight, the axis of the tube would also be the y-axis. The maximum deviation from straightness is the maximum distance between the y-axis and a measured centerpoint. Figure 4 shows how a given location, the centerpoint of the circle can deviate from center by coordinates (x,z).

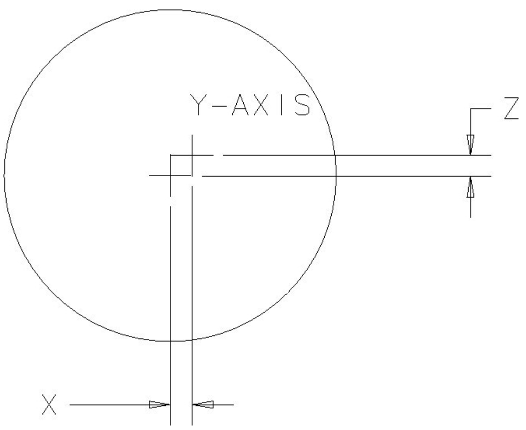

Figure 4 – Deviation of Tube from Straightness (the Y-Axis)

The deviation is calculated as the distance from the centerpoint to the y-axis:

$$\text{deviation} = \sqrt{X^2 + Z^2} \tag{4}$$

The deviation of mean diameter, as defined by the ANSI-H35.2-1993 standard for a drawn tube, is the difference between one-half of the sum of the outer diameters that are measured 90º apart and the specified outer diameter. Using Figure 5, the deviation is calculated as |25.8mm – 0.5*(AA+BB)|.

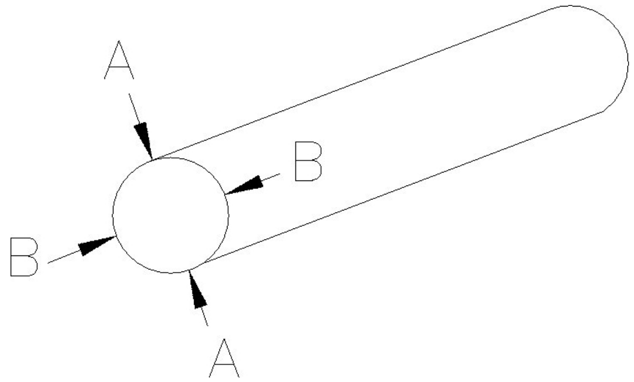

Figure 5 – Deviation of Mean Diameter from Specified Diameter

A clear line-of-sight is defined as the largest inner diameter of a perfectly straight cylinder that could pass through the entire length of the tube and whose axis is the same as the y-axis. For the line-of-sight, it is assumed that the wall thickness is 0.008 inch. Table 2 shows the results of the measurements. Since more than one set of measurements were taken with the tube in any orientation, the average values are shown.

Table 2 – Deviation from Straightness, Diameter, and Clear Line-of-Sight of Aluminum Tube Simply Supported at the Ends

Tube orientation	Average Max. Deviation from Straightness (mm)	Avg. Dev. of Mean Outer Dia. (mm)	Clear Line-of-Sight (mm)
Original position	5.0	0.030	15.4
90º from original	4.2	0.007	16.9
180º from original	2.5	0.108	20.1
270º from original	3.5	0.051	18.1

Table 3 lists the measurements of the tube when lying directly on the table. Two sets of measurements were taken with the tube in only one orientation. The numbers are compared with the ANSI standard for a drawn tube. The ANSI standard for straightness is applicable when the tube lies on a flat surface. The deviation of mean diameter and the clear line-of-sight are defined in the same way as in Table 2.

Table 3 – Deviation from Straightness, Diameter, and Clear Line-of-Sight of Aluminum Tube Lying Directly on Table

	Measured	ANSI-H35.2-1993
Avg. Max. Deviation from Straightness (mm)	1.4	3.0
Avg. Deviation of Mean Outer Diameter (mm)	0.09	0.13
Clear Line-of-Sight (mm)	22.5	--

Conclusions

The tube was made following industry standard for a drawn tube. Measurements of the tube show that the dimensional tolerances fall within the standard. The tube also sags a maximum of 5.0 mm (0.20 inch) at the middle of its length as expected. However, when the tube is simply supported at its ends, its largest clear line-of-sight can be as small as 15.4 mm (0.61 inch), depending on the orientation of the tube. For the BTeV beam line, the minimum allowable line-of-sight is 18 mm at a location 1 m from the interaction point C0. To ensure the beam can successfully clear the tube, the tube would have to be supported at least one place along its length. If the tube were supported at its ends and in the middle of its length so that there is 1485.9 mm (58.5 inches) between supports, using equations 1-3, the calculated sag in each unsupported section is 0.25 mm (0.01 inch). Assuming the same minimum outer diameter as measured (25.534 mm, or 1.005 inch), the clear line-of-sight would be 24.634 mm (0.97 inch). Thus, a tube that is supported at the middle of its length as a clear line-of-sight is large enough for the beam to pass.