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Review of BL4 Combination Magnet Coordinates

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Abstract: In this note we review the coordinates of BL4 combination magnet because there were noticeable discrepancies among legacy drawings and documents. Our goal is to reconcile the starting reference coordinate for the purpose of BL4N design.

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1 BL4N Combination Magnet Cross-Over Point

★**1.1** Look at the legacy document A-192, dated 8-Aug-1971, shown in Fig. 1, about the BL1 combination magnet (CM), where the so-called "Cross-over Point" (CoP), by definition, is the intersection of incoming beam axis with the outgoing beam axis.

This outgoing beam axis is fixed and constant, no matter what the incoming beam energy is. Thus, it's supposed to coincide with the axis of the beamline that follows (unless the beamline is tilted intentionally, for instance, in the old BL4 case).

Note that this outgoing beam axis is NOT the "MAG. SYMMETRY AXIS".

Also, note that this CoP is right sitting on the CM's centre-line.

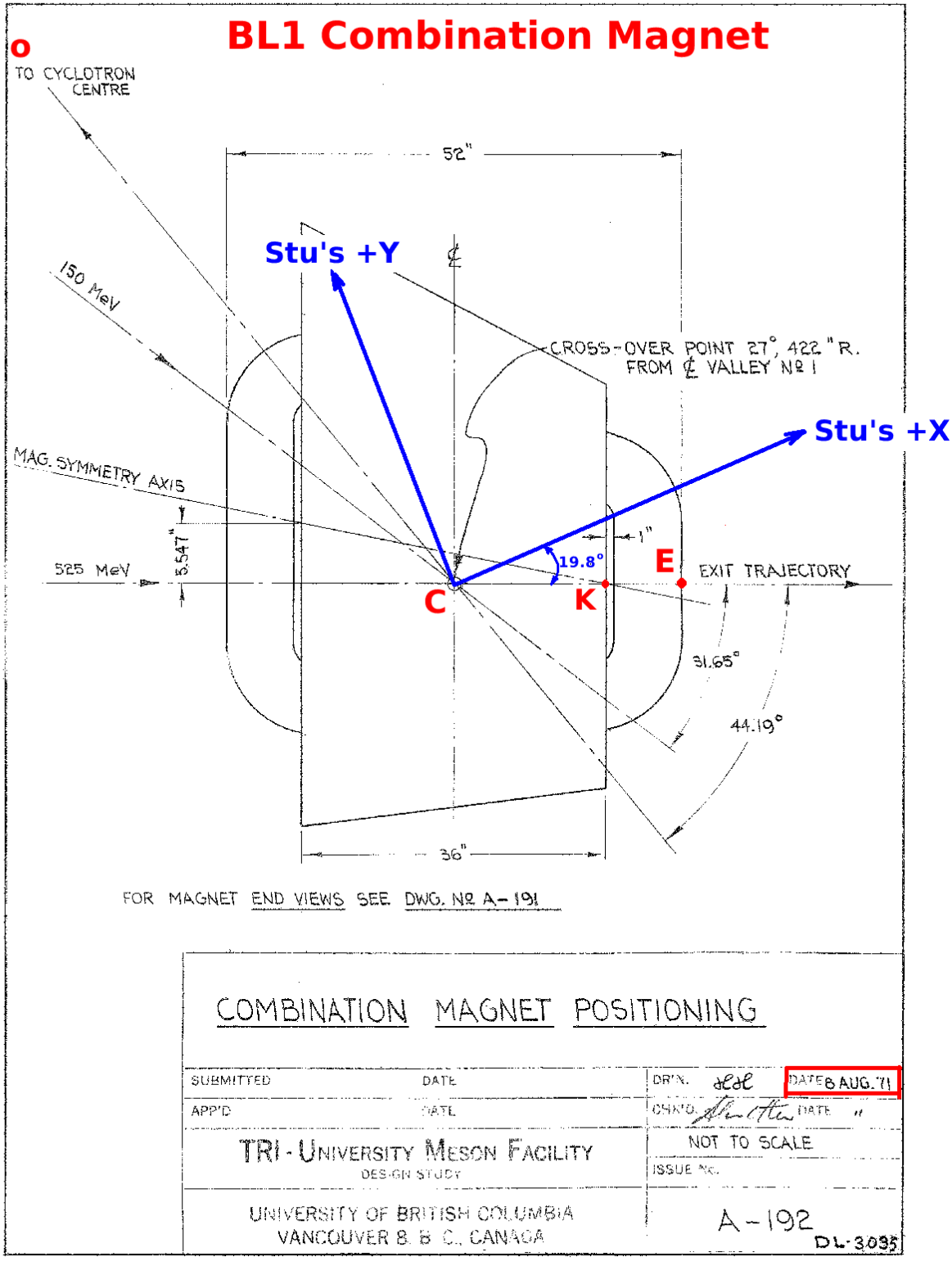


Figure 1: *A legacy document showing the orientation of the BL1 combination magnet, where the Stu's Cartesian frame X-C-Y has been parallelly shifted from the cyclotron centre O to the combination magnet cross-over point C, the points K and E respectively denote the intersections of the existing axis with the yoke edge and the winding edge in the geometrical median plane.*

★**1.2** From the Auto-CAD drawing TGN0207 rev.B (dated 22-Aug-2012), I measured the coordinate of the CoP of 4VCM1. It appears to be

$(x, y) = (-184.9926\,\text{inch} \quad +379.2911\,\text{inch})$.

This is equal to $(-4698.812\,\text{mm}, \quad +9633.994\,\text{mm})$.

Note that this CoP is explicitly marked with a circle on this drawing, and also the perpendicular distance from this point to the upstream edge of the CM yoke is 18.00", exactly identical to the perpendicular distance from this point to the downstream edge of the CM yoke. This means that this CoP is right sitting on the centre-line of the magnet.

On the other 2 drawings, namely TGN0206D rev.O (dated JUNE 2004) and TGN0205E rev.A (dated JUNE 2004) both, it's measured to be exactly the same as the above.

★**1.3** From the Auto-CAD drawing TSK0034_revB+52 (dated 07-Jul-2011) that Stu Austen created for the e-linac, I measured the CoP of BL4 CM which appears to be

$(x, y) = (-4.699\,\text{m}, \quad +9.634\,\text{m})$.

Apparently, this is just a round-off of the fore-mentioned figures. Thus, they are consistent too.

As well, this CoP is explicitly marked with a circle on this drawing, and the perpendicular distance from this point to the upstream edge of the CM yoke is 0.457 m (=18.00 inch), exactly identical to the perpendicular distance from this point to the downstream edge of the CM yoke. This means that this CoP is right sitting on the centre-line of the magnet.

★**1.4** On the legacy documents A-192 and TRI-DN-69-30 (see Fig. 1 and 2), they both show the CoP coordinate of 1VCM1 to be

(422 inch, 27° from centre-line of valley I).

Transforming this into Stu's Cartesian frame, I get

$$\begin{aligned} \mathrm{X} &= +422\,\text{inch} \quad \cos(91^\circ - 27^\circ) = +184.9926\,\text{inch} = +4698.81\,\text{mm}, \\ \mathrm{Y} &= -422\,\text{inch} \quad \sin(91^\circ - 27^\circ) = -379.2911\,\text{inch} = -9633.99\,\text{mm}. \end{aligned}$$

This is for the 1VCM1.

For 4VCM1, it is 180° apart w.r.t. the cyclotron centre according to George Clark. Thus, the 4VCM1 CoP is at

$$(\mathrm{x}, \mathrm{y}) = (-4698.81\,\text{mm}, +9633.99\,\text{mm}).$$

This is exactly consistent with the fore-mentioned too.

★★★ In conclusion, in terms of the drawings, the 4VCM1 CoP is located at

$(x, y) = (-4698.81\,\text{mm},\ +9633.99\,\text{mm})$.

This is defined in Stu's Cartesian frame (see Fig. 2), in which
the origin is in the centre of cyclotron;
+x axis is at 91° w.r.t. the centre-line of valley I;
+y axis is at 181° w.r.t. the centre-line of valley I;
+z axis points upward.

It's worthy to point out that +x axis is approximately (instead of exactly) pointing to East while +y axis is approximately (instead of exactly) pointing to North.

Furthermore, it's confirmed with T. Emmens that the +x axis is exactly parallel with the BL4N axis in the collimator section; while the +y axis is exactly parallel with the e-linac axis in the e-hall section, also exactly parallel with the e-line axis in the North-South tunnel section.

Bear in mind that the so-called Cross-over Point is meant the intersection of the incoming beam axis with the outgoing beam axis. The incoming beam axis differs for different extraction energies, while the outgoing beam axis is fixed and constant and supposed to be exactly along the CM's exiting axis.

★★★ While in terms of the legacy data files that C. Kost had been using for the `STRIPUBC` runs, the 4VCM1 CoP was given at

$(r,\ \theta) = (422.28'',\ 86.984°)$, instead of at $(r,\ \theta) = (422'',\ 87°)$.

Transforming this into Stu's Cartesian frame gives

$(x, y) = (r\ \cos(\theta + 29),\ r\ \sin(\theta + 29)) = (-4699.24\,\text{mm},\ 9641.70\,\text{mm})$.

This is offset from the above-mentioned drawing coordinate by -0.42 mm in x, and by $+7.71$ mm in y.

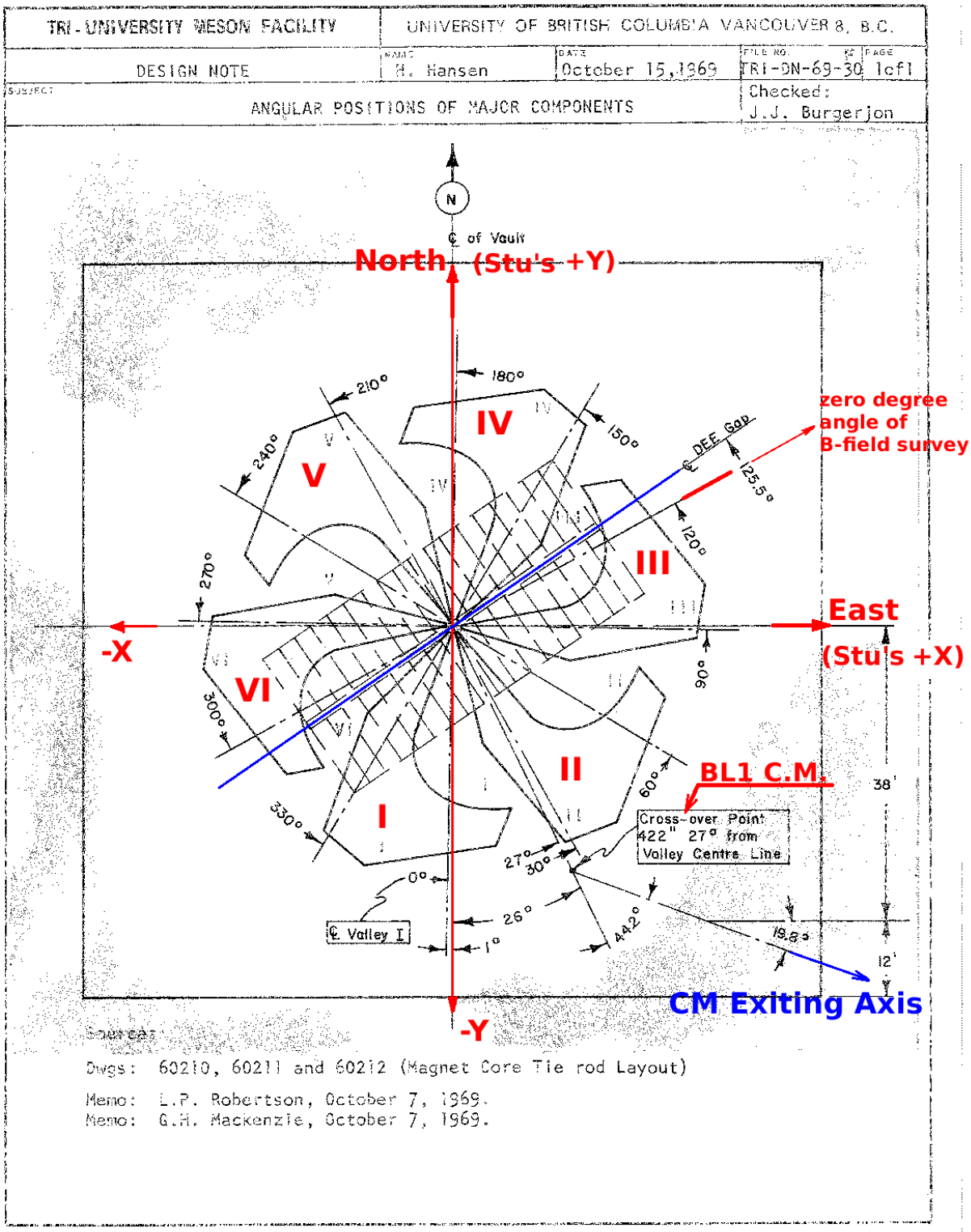


Figure 2: *A legacy document showing the cyclotron coordinate system and the BL1 CM coordinate.*

2 BL4N Combination Magnet Yoke Length

★**2.1** From Auto-CAD drawing TGN0207 rev.B (dated AUG-22-2012), I measured for the 4VCM1

(a) magnetic yoke length to be exactly 36.000 inch;
(b) winding length to be exactly 51.000 inch.

These 2 lengths are measured from edge to edge, exactly along the CM's exiting axis.

★**2.2** From Auto-CAD drawing D-32037 rev.F (dated JULY 86), I measured

(a) the perpendicular distance from 4VCM1 CoP to the yoke's edge (either edge) to be 18.000 inch;
(b) the perpendicular distance from 4VCM1 CoP to the winding edge (either edge) to be 25.500 inch.

These 2 distances are measured exactly along the CM's exiting axis.

★**2.3** The BL4 CM was ever re-shimmed according to George Clark, who helped dig out a document, titled

"A REVIEW OF THE MODIFICATIONS TO COMBINATION MAGNET CM4",

authored by Alan Otter & Jim McIlroy, dated Dec. 1982.

In section 2.4 of this document there is a description of how and why the gap of CM4 was changed, that is,

"It was decided to install an additional shim between the upper pole and yoke of the magnet to reduce the gap. This would give a higher field value for the same current. It also lowers the magnetic median plane closer to that of the Beamline 4 median plane.

A 0.125 inch shim was requested but a sheet of steel of this thickness was not available. Sheet nominally 0.105 inch thick was used and the gap was measured using an internal micrometer.

Gap prior to shimming	3.745 in.
Gap after shimming	3.634 in.
change	0.111 in.

With this change we expect that the values of current required should be scaled down in the ratio of 3.634/3.745 or 0.9704 for each tune. This change may also allow the cyclotron output energy range to be extended slightly."

Nevertheless, there was no change made to the yoke and winding.

★★★ In conclusion, the 4VCM1 yoke's length is 36.000 inch, and the winding length is 51.000 inch instead of 52.000 inch. The 52.000 inch is the winding length of the BL1 CM.

3 BL4N C.M. Winding Edge

★**3.1** Because the documents A-192 & TRI-DN-69-30 exist for the 1VCM1 (shown in Fig. 1 and 2), with dimensions and angles indicated explicitly, it's straightforward to begin with 1VCM1 to work out the coordinates of interest.

My objective is to determine the coordinate of point E, the intersection between the exiting axis and the winding edge in the GMP, as shown in the Fig. 1.

Since

$$\overline{OC} = 422'', \quad \overline{CE} = 26'' \quad \text{and} \quad \angle OCE = 180° - 44.19° = 135.81°,$$

thus

$$\begin{aligned}\overline{OE} &= \sqrt{\overline{OC}^2 + \overline{CE}^2 - 2\,\overline{OC}\,\overline{CE}\,\cos(\angle OCE)} \\ &= \sqrt{422^2 + 26^2 - 2 \times 422 \times 26\,\cos 135.81°} \\ &= 441.0154'' \ .\end{aligned}$$

While

$$\frac{\overline{OE}}{\sin(\angle OCE)} = \frac{\overline{CE}}{\sin(\angle COE)}$$

so

$$\sin(\angle COE) = \frac{\overline{CE}\sin(\angle OCE)}{\overline{OE}} = \frac{26\ \sin 135.81°}{441.0154} = 0.04109$$

thus $\angle COE = 2.3552°$.

That is, the point E is at $27° + 2.3552° = 29.3552°$ from the centre-line of valley I.

So, in the polar coordinate system used for TRIUMF B-field survey, the point E is sitting at

R $= \overline{OE} = 441.0154''$,
$\theta = -(120° - 29.3552°) = -90.6448° = 269.3552°$ (see Fig. 2).

Transform this into Stu's Cartesian frame, I get the point E coordinate:

$$X_{E1} = R\cos(\theta + 29) = 441.0154'' \cos(269.3552^\circ + 29^\circ) = 209.4540'',$$

$$Y_{E1} = R\sin(\theta + 29) = 441.0154'' \sin(269.3552^\circ + 29^\circ) = -388.1025''.$$

But, this is not the end of story.

★3.2 In all the data files that Corrie Kost used for the STRIPUBC runs, the CoP for the BL1 CM was given, in the polar frame for the B-field survey, as (422.28″, 266.984°), instead of (422″, 267°).

And the angle between the exiting axis of CM with the radial line through the CM's CoP was given as 44.34°, instead of the above 44.19°.

For the BL4 CM, the CoP was given at (422.28″, 86.984°)
instead of at (422″, 87°).

As well, the angle was 44.34° instead of 44.19°.

It's unclear to me where these 3 figures were coming from, but they had been used in all the legacy files for the STRIPUBC runs. I just inherited them without any grounds to change them.

Here I presume that the coordinate (422.28″, 266.984°) and the angle of 44.34° are correct. And then, I repeated the above calculations to work out the coordinate of point E. The result is

$$X_{E2} = R\cos(\theta + 29) = 441.2497'' \cos(269.34425^\circ + 29^\circ) = 209.4913'',$$

$$Y_{E2} = R\sin(\theta + 29) = 441.2497'' \sin(269.34425^\circ + 29^\circ) = -388.3487''.$$

Compare with the previous one:

$X_{E1} = 209.4540''$,
$Y_{E1} = -388.1025''$.

It's seen that mainly in Y direction they offset by $0.246'' = 6.3\,\text{mm}$.

★★★ Taking an average of these two points gives

$X_E = (X_{E1}+X_{E2})/2 = (209.4913''+209.4540'')/2 = +209.4727'' = +5320.6\,\text{mm},$
$Y_E = (Y_{E1}+Y_{E2})/2 = (-388.3487''-388.1025'')/2 = -388.2256'' = -9861.0\,\text{mm}.$

Finally, symmetrize it, giving the point E for BL4N:

$(X_E,\, Y_E) = (-5320.6\,\textbf{mm},\quad +\textbf{9861.0 mm}).$

Remember that this point E is meant at $26''$ from the BL4 CM centre-line, rather than at $25.5''$.

Notice that this coordinate has a considerable offset from the fore-mentioned starting coordinate ($-5311.0\,\text{mm},\ \ 9829.6\,\text{mm}$) that Stu marked on his drawings.

This offset is NOT along the exiting axis of the CM, instead, it's along a line angling wrt Stu's X-axis by

$\alpha = atan(dY/dX) = atan((9861.0 - 9829.6)/(-5320.6 + 5311.0)) = 107°.$

While the exiting axis of CM is angling with Stu's X-axis by $180° - 19.8° = 160.2°$. See Fig. 1 and 2.

In brief, Stu's starting point of

$(X, Y) = (-5.3110\,\textbf{m},\ \textbf{9.8296 m}) = (-5311.0\,\textbf{mm},\ \textbf{9829.6 mm})$

is NOT sitting on the exiting axis of BL4 CM. Maybe he picked up the mid-point of the vacuum box as the starting point, but that is not right, because we should consider the CM exiting axis to be the reference trajectory of the new BL4N.

4 BL4N C.M. Yoke Edge

The point K is the intersection of CM exiting axis with the downstream edge of the yoke in the GMP.

★4.1 Use the numerical values indicated in A-192.

Since

$$\overline{OC} = 422", \quad \overline{CK} = 18" \quad \text{and} \quad \angle OCK = 180° - 44.19° = 135.81°,$$

thus

$$\begin{aligned}\overline{OK} &= \sqrt{\overline{OC}^2 + \overline{CK}^2 - 2\,\overline{OC}\,\overline{CK}\,\cos(\angle OCK)} \\ &= \sqrt{422^2 + 18^2 - 2 \times 422 \times 18\,\cos 135.81°} \\ &= 435.0875" \ .\end{aligned}$$

While

$$\frac{\overline{OK}}{\sin(\angle OCK)} = \frac{\overline{CK}}{\sin(\angle COK)}$$

so

$$\sin(\angle COK) = \frac{\overline{CK}\sin(\angle OCK)}{\overline{OK}} = \frac{18'' \times \sin 135.81°}{435.0875''} = 0.028837$$

thus $\angle COK = 1.6525°$.

That is, the point K is at $27° + 1.6525° = 28.6525°$ w.r.t. Valley I Centre-line.

So, in the polar coordinate system used for TRIUMF B-field survey, the point K is sitting at

R $= \overline{OK} = 435.0875"$,
$\theta = -(120° - 28.6525°) = -91.3475° = 268.6525°$.

Transform this into Stu's Cartesian frame, I get

$$X = R\,\cos(\theta + 29) = 435.0875\,\cos(268.6525° + 29°) = 201.9274",$$

$$Y = R\,\sin(\theta + 29) = 435.0875\,\sin(268.6525° + 29°) = -385.3912".$$

Symmetrize it for BL4 CM, giving

$(X_{k1},\, Y_{k1}) = (-201.9274'',\, +385.3912'')$=$(-5128.96\,\text{mm}, +9788.94\,\text{mm})$

★4.2 Use C. Kost's data that he used for STRIPUBC runs. I repeated the above calculations to work out the coordinate of point K. The result is

$$X_{k2} = R\,\cos(\theta + 29) = 435.3355''\,\cos(268.63998^\circ + 29^\circ) = 201.9584'',$$

$$Y_{k2} = R\,\sin(\theta + 29) = 435.3355''\,\sin(268.63998^\circ + 29^\circ) = -385.6550''.$$

Symmetrize it for BL4 CM, giving

$(X_{k2},\, Y_{k2}) = (-201.9584'',\, +385.6550'')$ =$(-5129.74\,\text{mm}, +9795.64\,\text{mm})$.

★ 4.3 Take an average of the above 2 points (X_{k1}, Y_{k1}),(X_{k2}, Y_{k2}) to get their mid-point:

$$X_k = \frac{X_{k1} + X_{k2}}{2} = \frac{-201.9274'' - 201.9584''}{2} = -201.9429'' = -5129.35\,\text{mm},$$

$$Y_k = \frac{Y_{k1} + Y_{k2}}{2} = \frac{+385.3912'' + 385.6550''}{2} = +385.5231'' = +9792.29\,\text{mm}.$$

★★★ Eventually, Design Office T. Emmens reconciled the coordinates. He stated that "Bruno, Mike and Myself have checked the co-ordinates of the BL4N combination magnet and have determined that the best estimate of position is based on calculations derived from information on drawing A-192 and as measured dimensions from actual vault surveys. We have converged to within 0.6 mm. There are some physical discrepancies such as the actual width of the yoke piece, specified as 36.00 inch but measured at approx. 36.125 inch wide and the exact location of the cyclotron centre as measured by alignment crew.

The co-ordinate positions are as follows.

1. Cross over point on Combination Magnet E-126:

$$X_C = -4698.81\,\textbf{mm}, \quad Y_C = 9633.99\,\textbf{mm};$$

2. Edge of yoke at 90 degree line from CoP:

$$X_K = -5126.83\,\textbf{mm}, \quad Y_K = 9794.84\,\textbf{mm}.$$

This line is 20.06° from Cartesian grid line X. See attachment (schematic diagram below). We feel our co-ordinate position numbers are accurate within ±3 mm."

In summary, Tim winds up giving an exactly the same coordinate of CoP as the legacy drawings, but his "edge of yoke" coordinate, i.e. the point K, is shifted from my average value by +2.52 mm along $+X$, as well as +2.55 mm along $+Y$, further away from the cyclotron centre by 1.1 mm. Nevertheless, this shift is small; we don't worry about it.

JUNE 19 '2019 T. LEMMENS. MIKE VOGEL BRUNO GASBARRI

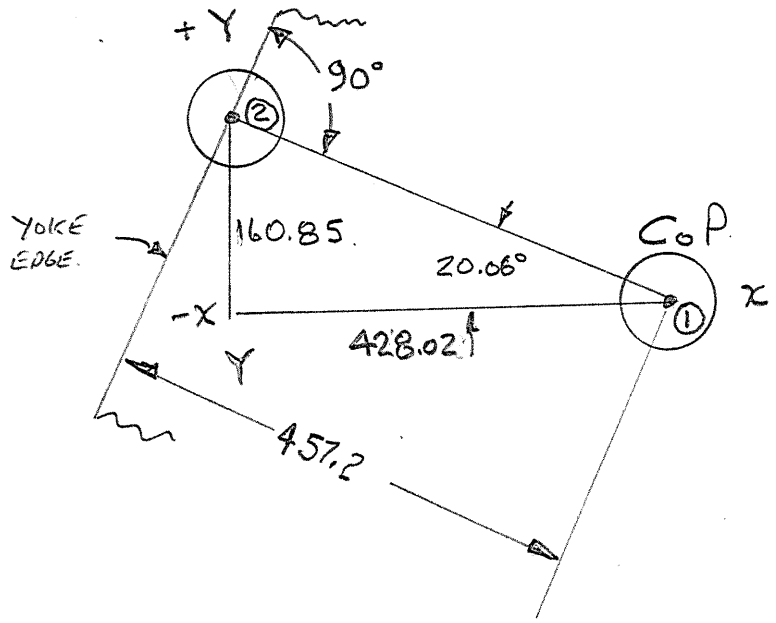
FOR YI-NONG.

COMBI CoP CO-ORDS FROM A-192.

LEDGE OF YOKE & TO BEAM CO-ORDS.

FROM TEL1814-4 ① CoP X = -4698.81. Y = 9633.99.

② PERP-TO YOKE EDGE X = -5126.83 Y = 9794.84.



5 BL4N Starting Point

I define the BL4N starting point S as the terminus of the reference trajectory of 480 MeV proton, calculated with `STRIPUBC`, through the cyclotron fringe field, exit horn and the combination magnet; it's exactly sitting on the combination magnet exiting axis at a distance of $26.80'' = 680.72$ mm from the CoP.

This means that its coordinate $S(X_S\ Y_S)$ must satisfy the following two equations:

$$\frac{Y_S - Y_C}{X_S - X_C} = \frac{Y_K - Y_C}{X_K - X_C}\ ,$$

$$\sqrt{(X_S - X_C)^2 + (Y_S - Y_C)^2} = 680.72$$

Inserting Tim's coordinates

$$(X_C,\ Y_C) = (-4698.81\,\text{mm},\ 9633.99\,\text{mm}) \text{ and}$$
$$(X_K,\ Y_K) = (-5126.83\,\text{mm},\ 9794.84\,\text{mm})$$

gives

$$(X_S,\ Y_S) = (-5336.02\,\textbf{mm},\ 9873.45\,\textbf{mm}).$$

Note that solving these two equations produces 2 different solutions. The correct one should be the point that is farther away from the cyclotron centre.

It appears that Tim's CoP and my starting point S both are closely sitting on the `STRIPUBC` calculated reference trajectory. This is shown in Fig. 3 and Fig. 4. But, in fact they are NOT exactly the same: the `STRIPUBC's` CoP is sitting at $(x_c,\ y_c) = (-4699.24\,\text{mm},\ 9641.70\,\text{mm}$, shifted from Tim's CoP by $(\Delta x_c = -0.43\,\text{mm},\ \Delta y_c = 7.71\,\text{mm})$; the `STRIPUBC` calculated reference trajectory of 480 MeV is ending at $(x_s,\ y_s) = (-5338.97\,\text{mm},\ 9870.51\,\text{mm})$, shifted from the above point S by $(\Delta x_s = -2.95\,\text{mm},\ \Delta y_s = -2.94\,\text{mm})$. These offsets are too small to be appreciable in the scale of Figs. 3 and 4.

In conclusion, the coordinate positions that Tim eventually proposes for the CoP, for the yoke edge point K as well as for the BL4N starting point S are close enough to the reference trajectory that I calculated using `STRIPUBC`. This is a gratifying result.

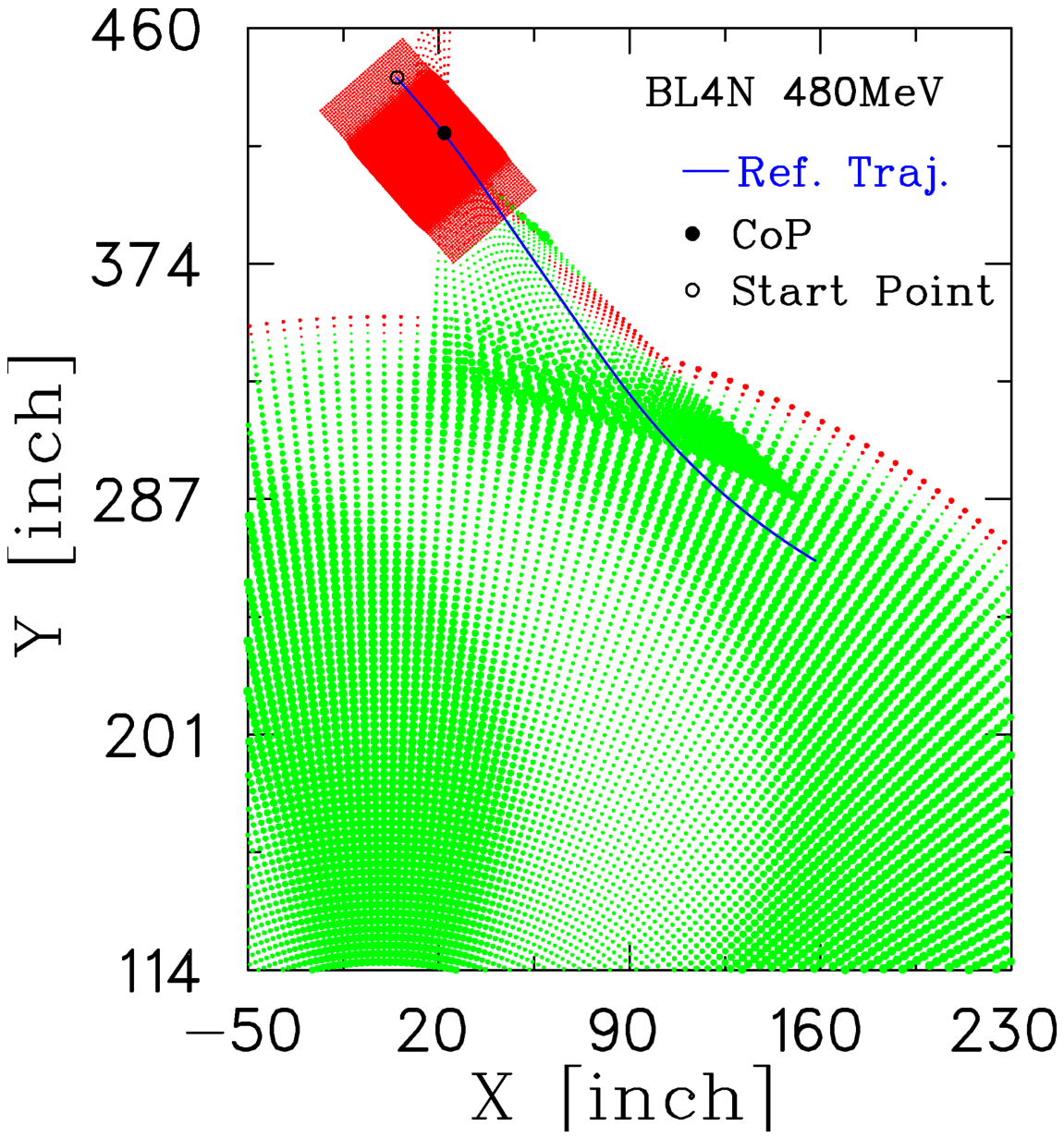


Figure 3: `STRIPUBC` *calculated reference trajectory of 480 MeV proton passing through the cyclotron fringe field, the exit horn and the combination magnet. The marked CoP and Start Point are the coordinate positions given by Tim; they appear to be closely sitting on the reference trajectory.*

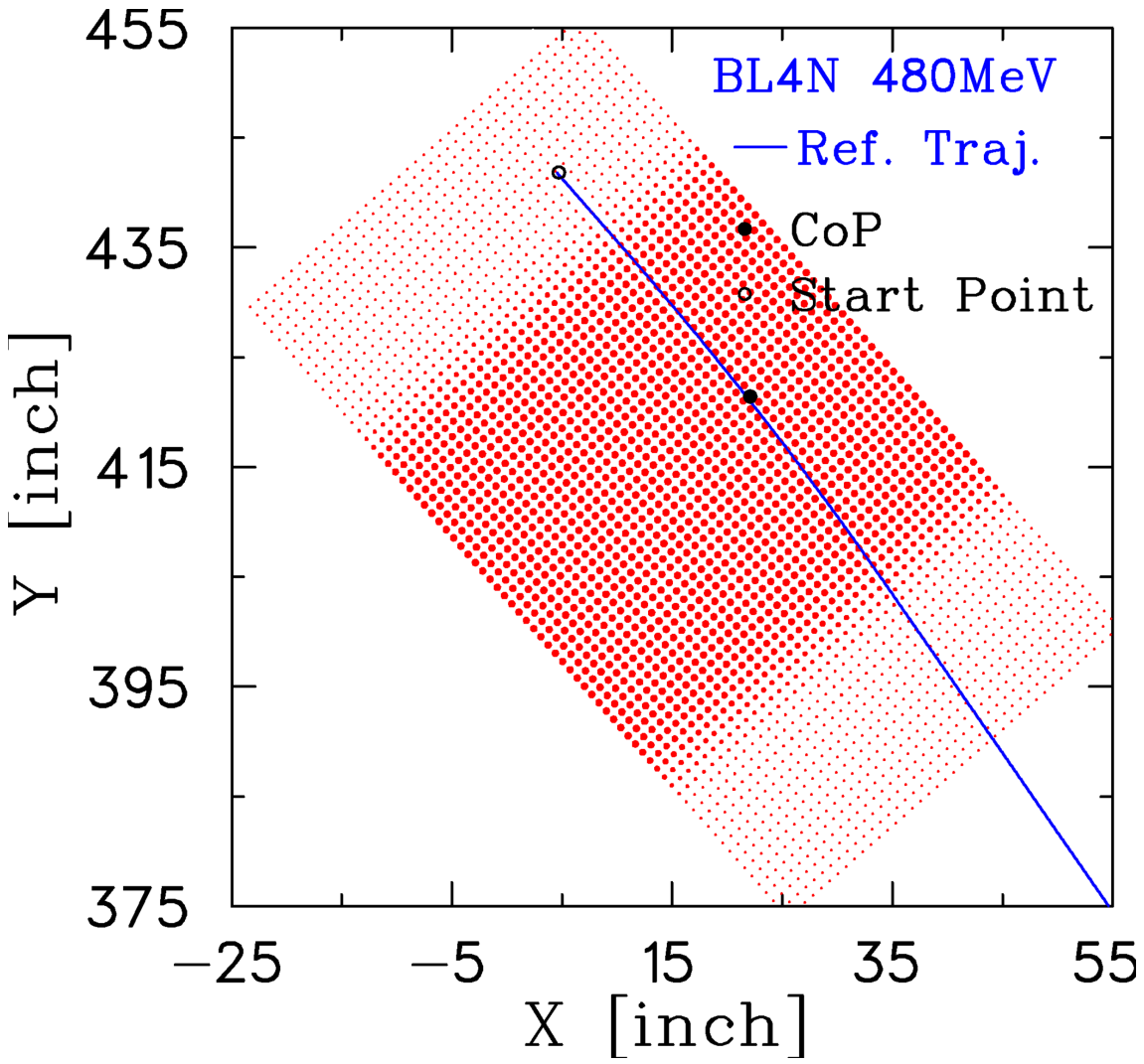


Figure 4: *Zoom-in of the 480 MeV reference trajectory passing through the combination magnet. The marked CoP and Start Point are the coordinate positions given by Tim; they appear to be closely sitting on the reference trajectory.*