**TRIUMF Beam Physics Note**
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# Requirement Specifications for BL4N Extraction Stripping Foil's Locus

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**Abstract:** In this note I give specifications for the BL4N extraction stripping foil's locus after reviewing the old beamline 4's situation.

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# 1 Top Level Requirements

The beamline 4N (BL4N) shall be solely used to provide proton beam from the extraction port #4 of TRIUMF cyclotron to the ARIEL target [1]. As such, it's required that the energy range [2] of beam extracted be the same as that of the existing BL2A, that is, between 475 and 500 MeV. Over this energy range, the stripping foil's positions must be such that the reference trajectories of the extracted beam come in through the cross-over point of the combination magnet, and exit out of the axis of the combination magnet with zero degree angle and then go straight down to the beamline.

The stripping foil's positions are calculated by tracking of particle with the computer code `STRIPUBC` [3], and are represented in $(r,\, \theta)$ in the cyclotron polar coordinate system. These $(r,\, \theta)$ coordinates are then transformed into the extraction probe's coordinates $(R,\, L)$, with which cyclotron operators can move the stripping foil from console through the control system. Since the BL4N extraction port maintains the same as the old beamline 4 (BL4) except that BL4N has a narrower energy range of beam than the BL4, it's worthy to review the BL4 extraction foil's locus as a checkup and also as a reference for the BL4N.

# 2 Review

Around 1986, the old BL4 downstream of the combination magnet exit was rotated [4] by $-5°$ to make room for the longitudinal polarization solenoids, but the combination magnet was not moved or changed on purpose since day one [5]. This $-5°$ rotation means that the BL4 axis was at $5°$ to the right of the combination magnet axis [6] [7]. After the rotation, the BL4 was never rotated back to the original angle till it was dismantled.

The beamline 4B production tunes after Nov. 1986 were saved and labelled in a binder [8] by the experimenter. Out of which, I retrieved the data of $(R,\, L)$ coordinate operational settings for the stripping foil as well as the data of combination magnet's excitations. These are shown in Fig.1 for various energies between 350 and 510 MeV, together with the theoretical values. (The beamline was actually running between 180 and 510 MeV.) Overall the operational settings agree well with the theoretical values in both $R$ and $L$; the $L's$ do not agree as well as the $R's$, though.

The theoretical values of $(R,\, L)$ were calculated using formulas for the transformation from $(r, \theta)$ to $(R,\, L)$. The $(r, \theta)$ values were calculated with `STRIPUBC` and are listed in Table 1. The transformation is represented in details in the following, based on the geometrical correlation between these two frames as sketched in the diagram Fig.2.

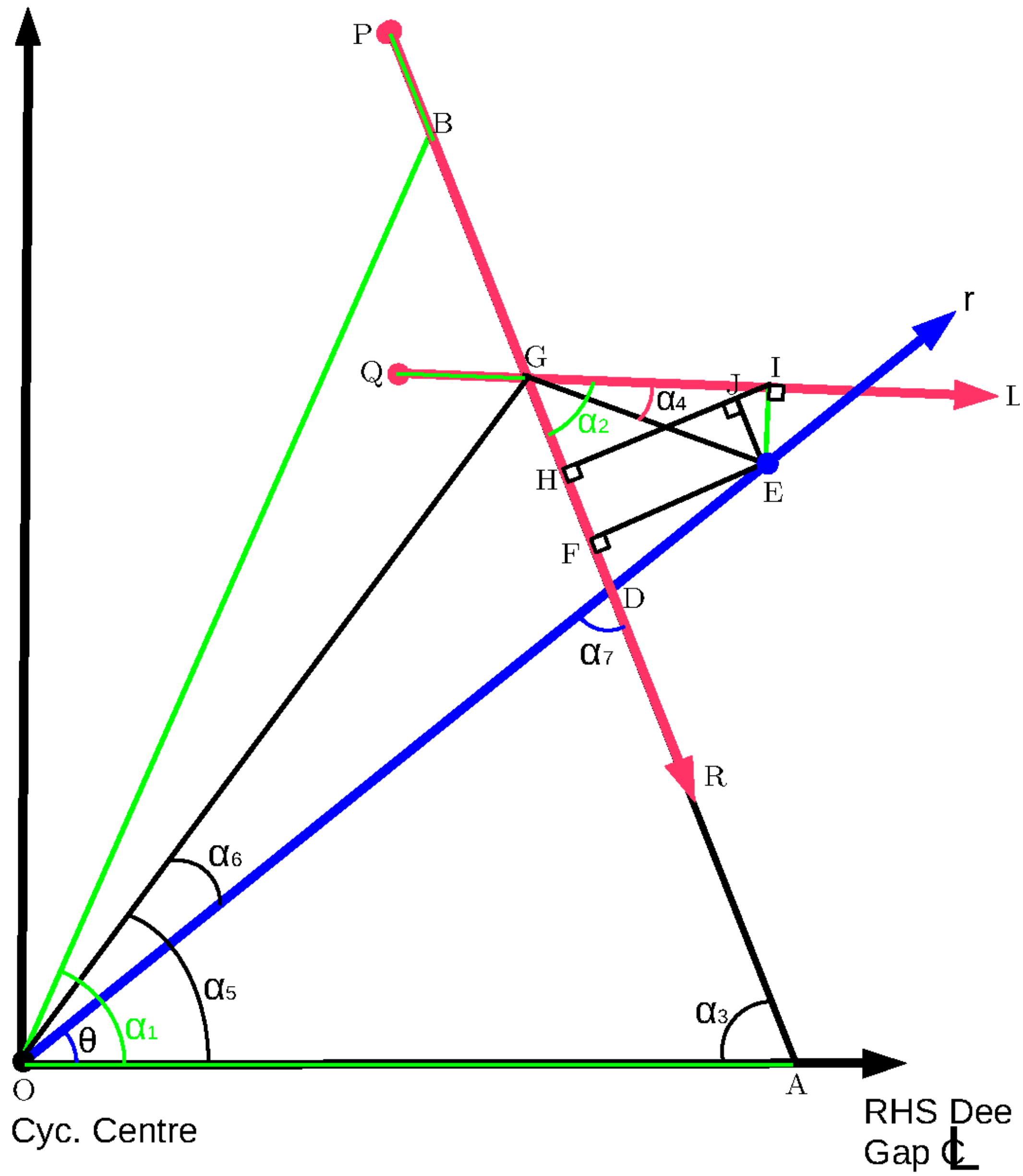


Figure 1: *Schematic diagram showing geometrical correlation between the old BL4 probe's coordinates* $(R, L)$ *and the cyclotron polar coordinates* $(r, \theta)$. *The points* $P$ *and* $Q$ *denote the pivots of probe arms along the* $R$ *and* $L$ *paths respectively, in other words, they are the origins of* $R$ *and* $L$ *axes. Note that* $r = \overline{OE}$, $R = \overline{PG}$ *and* $L = \overline{QI}$. *Also note that the green-colored line segments and angles namely* $\overline{OA}$, $\overline{OB}$, $\overline{PB}$, $\overline{QG}$, $\overline{EI}$, $\alpha_1$ *and* $\alpha_2$ *are known parameters as they were measured priorly.*

$$R \equiv \overline{PG} = \overline{PB} + \overline{BG} = \overline{PB} + (\overline{BA} - \overline{GD} - \overline{DA}) \, ,$$

$$L \equiv \overline{QI} = \overline{QG} + \overline{GI} = \overline{QG} + \frac{\overline{HI}}{\sin \alpha_2} \ ,$$

in which

$$\overline{BA} = \sqrt{\overline{OA}^2 + \overline{OB}^2 - 2\,\overline{OA}\,\overline{OB}\ \cos \alpha_1} \ ,$$

$$\overline{GD} = \overline{GH} + \overline{HF} + \overline{FD} = \overline{HI}\ \cos \alpha_2 + \overline{EI}\ \sin \alpha_2 + \overline{DE}\ \cos \alpha_7 \, ,$$

$$\overline{HI} = \overline{HJ} + \overline{JI} = \overline{DE}\ \sin \alpha_7 + \overline{EI}\ \cos \alpha_2 \ \ , \ \ \overline{DE} = \overline{OE} - \overline{OD} = r - \overline{OD} \ ,$$

$$\overline{OD} = \frac{\overline{OA}\ \sin \alpha_3}{\sin \alpha_7} \ \ , \ \ \overline{DA} = \frac{\overline{OA}\ \sin \theta}{\sin \alpha_7} \ ,$$

$$\alpha_7 = 180^\circ - \theta - \alpha_3 \ \ , \ \ \alpha_3 = \arccos\left(\frac{\overline{OA}^2 + \overline{BA}^2 - \overline{OB}^2}{2\,\overline{OA}\,\overline{BA}}\right) \ ,$$

where $\overline{OA} = 132.52''$, $\overline{OB} = 336.47''$, $\overline{PB} = 37.44''$ (offset in R), $\overline{QG} = 3.38''$ (offset in L), $\overline{EI} = 0.075''$ (offset of the foil), $\alpha_1 = 57.1^\circ$ and $\alpha_2 = 57.0^\circ$ are known geometrical parameters as they were measured priorly. Note that the $\theta$ is meant relative to the cyclotron right hand side Dee gap centre-line.

Reversely, the transformation from $(R,\ L)$ to $(r, \theta)$ is represented as follows.

$$r \equiv \overline{OE} = \sqrt{\overline{OG}^2 + \overline{GE}^2 - 2\,\overline{OG}\,\overline{GE}\ \cos(\angle EGO)} \ ,$$

$$\theta = \begin{cases} \alpha_5 - \alpha_6 & , \ \alpha_6 \geq 0 \\ \alpha_5 + \alpha_6 & , \ \alpha_6 < 0 \end{cases} \ ,$$

in which

$$\overline{OG} = \sqrt{\overline{OA}^2 + \overline{AG}^2 - 2\,\overline{OA}\,\overline{AG}\ \cos \alpha_3} \ ,$$

$$\overline{AG} = \overline{PB} + \overline{BA} - \overline{PG} = \overline{PB} + \overline{BA} - R \ \ ,$$

$$\overline{BA} = \sqrt{\overline{OA}^2 + \overline{OB}^2 - 2\,\overline{OA}\,\overline{OB}\,\cos\alpha_1} \ ,$$

$$\overline{GE} = \sqrt{\overline{GI}^2 + \overline{EI}^2} \ , \ \ \overline{GI} = \overline{QI} - \overline{QG} = L - \overline{QG} \ ,$$

$$\alpha_3 = \arccos\left(\frac{\overline{OA}^2 + \overline{BA}^2 - \overline{OB}^2}{2\,\overline{OA}\,\overline{BA}}\right) \ ,$$

$$\alpha_5 = \arccos\left(\frac{\overline{OG}^2 + \overline{OA}^2 - \overline{AG}^2}{2\,\overline{OG}\,\overline{OA}}\right) \ ,$$

$$\alpha_4 = \begin{cases} \arctan\left(\overline{EI}/\overline{GI}\right) & , \ \text{if } \overline{EI} \neq 0 \text{ or } \overline{GI} \neq 0 \\ 0 & , \ \text{otherwise} \end{cases} \ ,$$

$$\angle EGO = 180^\circ - \alpha_5 - \alpha_3 + \alpha_2 - \alpha_4 \ ,$$

$$\alpha_6 = \arccos\left(\frac{\overline{OG}^2 + r^2 - \overline{GE}^2}{2\,\overline{OG}\,r}\right) \ .$$

These formulas clearly show that the $r$ and $\theta$ coordinates both are coupled with the $R$ and $L$ values. This implies that any deviation in $L$ from its theoretical value (as shown in the Fig.1) will cause a shift in both the $r$ and $\theta$ coordinates, even though the $R$ value remains unchanged from the theoretical value. This is illustrated in Fig.3 for an offset of $L = \pm 25\%$. But should be pointed out that such a shift in the $r$ and $\theta$ takes place unnecessarily along the equilibrium orbit, so the energy of beam extracted can shift a bit ($\sim \pm 0.3\%$). The abscissa in Fig.3 is just meant the "nominal" energy.

# 3 BL4N Extraction Foil Locus

The above review gives us confidence that the `STRIPUBC` calculated stripping foil's positions are accurate enough. Therefore, we proceed with calculations to determine the extraction foil's locus for the BL4N, where the beam shall be exiting out of the combination magnet axis with zero degree angle. The results are contained in the Table 1.

Table 1: STRIPUBC calculated extraction stripping foil's locus under conditions that the beam exits at $-5°$ (in the old beamline 4 case) and at $0°$ (for the BL4N) resp. w.r.t. the combination magnet axis. Note that the origin of the coordinate system is in the center of cyclotron; $+x$ axis, on which $\theta = 0°$, is directing to the right-hand side Dee gap center line while $+y$ axis is $90°$ counterclockwise rotation from $+x$ axis.

| p-beam energy (MeV) | $-5°$ exit | | $0°$ exit for BL4N | | | |
|---|---|---|---|---|---|---|
| | r (inch) | $\theta$(degr) | r(inch) | $\theta$(degr) | x(inch) | y(inch) |
| 449.510 | 302.859 | 53.928 | 302.886 | 53.501 | 180.159 | 243.480 |
| 453.506 | 303.551 | 53.941 | 303.574 | 53.510 | 180.530 | 244.062 |
| 457.501 | 304.249 | 53.954 | 304.268 | 53.521 | 180.896 | 244.654 |
| 459.499 | 304.599 | 53.960 | 304.616 | 53.527 | 181.077 | 244.953 |
| 461.497 | 304.948 | 53.968 | 304.963 | 53.532 | 181.262 | 245.248 |
| 463.495 | 305.297 | 53.975 | 305.310 | 53.537 | 181.447 | 245.543 |
| 465.493 | 305.644 | 53.982 | 305.654 | 53.544 | 181.621 | 245.842 |
| 467.490 | 305.990 | 53.986 | 305.999 | 53.549 | 181.805 | 246.135 |
| 469.488 | 306.336 | 53.993 | 306.343 | 53.555 | 181.983 | 246.431 |
| 470.487 | 306.509 | 53.998 | 306.515 | 53.560 | 182.064 | 246.585 |
| 472.485 | 306.856 | 54.003 | 306.859 | 53.566 | 182.242 | 246.881 |
| 473.484 | 307.029 | 54.008 | 307.032 | 53.569 | 182.332 | 247.030 |
| 474.483 | 307.203 | 54.012 | 307.204 | 53.573 | 182.417 | 247.181 |
| 475.482 | 307.376 | 54.014 | 307.376 | 53.576 | 182.506 | 247.329 |
| 477.480 | 307.721 | 54.021 | 307.719 | 53.583 | 182.680 | 247.627 |
| 479.477 | 308.063 | 54.029 | 308.059 | 53.590 | 182.851 | 247.923 |
| 480.476 | 308.233 | 54.032 | 308.228 | 53.593 | 182.939 | 248.068 |
| 481.475 | 308.402 | 54.035 | 308.396 | 53.597 | 183.021 | 248.216 |
| 483.473 | 308.737 | 54.042 | 308.729 | 53.601 | 183.201 | 248.497 |
| 485.471 | 309.069 | 54.048 | 309.059 | 53.609 | 183.362 | 248.788 |
| 487.469 | 309.398 | 54.055 | 309.386 | 53.615 | 183.530 | 249.071 |
| 489.466 | 309.726 | 54.060 | 309.712 | 53.620 | 183.702 | 249.349 |
| 491.464 | 310.052 | 54.066 | 310.037 | 53.626 | 183.869 | 249.630 |
| 493.462 | 310.378 | 54.072 | 310.361 | 53.632 | 184.035 | 249.910 |
| 495.460 | 310.703 | 54.079 | 310.684 | 53.637 | 184.204 | 250.187 |
| 496.459 | 310.865 | 54.081 | 310.845 | 53.640 | 184.287 | 250.326 |
| 497.458 | 311.027 | 54.084 | 311.006 | 53.642 | 184.373 | 250.462 |
| 498.457 | 311.188 | 54.086 | 311.166 | 53.645 | 184.455 | 250.601 |
| 499.456 | 311.349 | 54.090 | 311.326 | 53.648 | 184.537 | 250.739 |
| 500.454 | 311.510 | 54.092 | 311.486 | 53.650 | 184.623 | 250.874 |
| 501.453 | 311.670 | 54.094 | 311.646 | 53.653 | 184.705 | 251.013 |
| 503.451 | 311.989 | 54.101 | 311.963 | 53.658 | 184.870 | 251.284 |
| 505.449 | 312.306 | 54.104 | 312.278 | 53.662 | 185.040 | 251.551 |
| 507.447 | 312.623 | 54.108 | 312.593 | 53.666 | 185.209 | 251.818 |
| 509.445 | 312.942 | 54.112 | 312.911 | 53.669 | 185.384 | 252.084 |
| 511.443 | 313.266 | 54.116 | 313.233 | 53.672 | 185.561 | 252.353 |

# References


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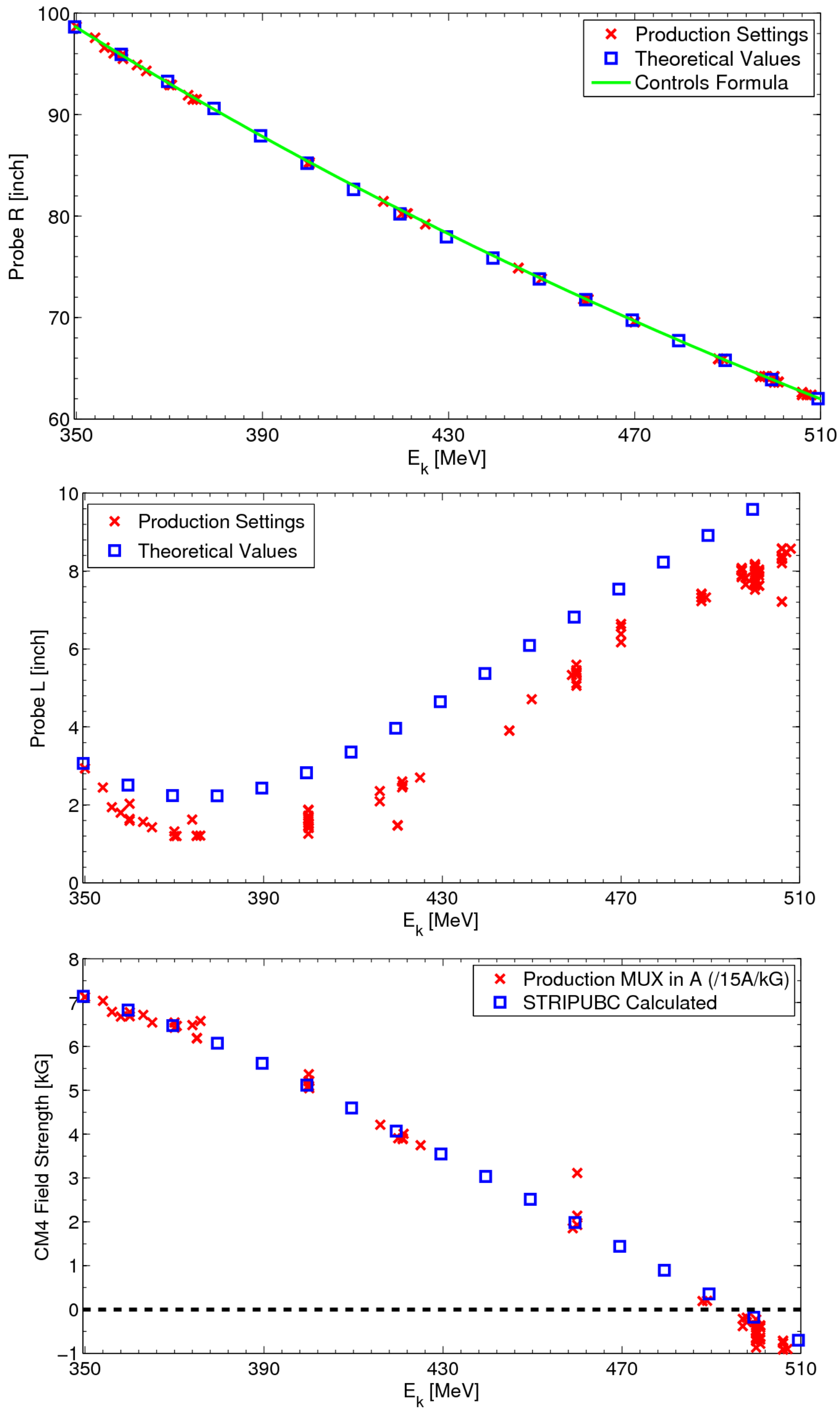


Figure 2: *The old BL4 extraction probe's coordinates in R (Top) and L (Middle) and the combination magnet excitation (Bottom) vs. the energy of beam extracted. Note that the "Controls Formula" means this is the result calculated with a formula coded in the control's software [9] for the BL4, namely,* $E_k = (-19.051 + (0.21586 + (-1.6349 \times 10^{-3} + (6.81347 \times 10^{-6} + (-1.15631 \times 10^{-8}) \times R) \times R) \times R) \times R) \times R + 1160.8$.

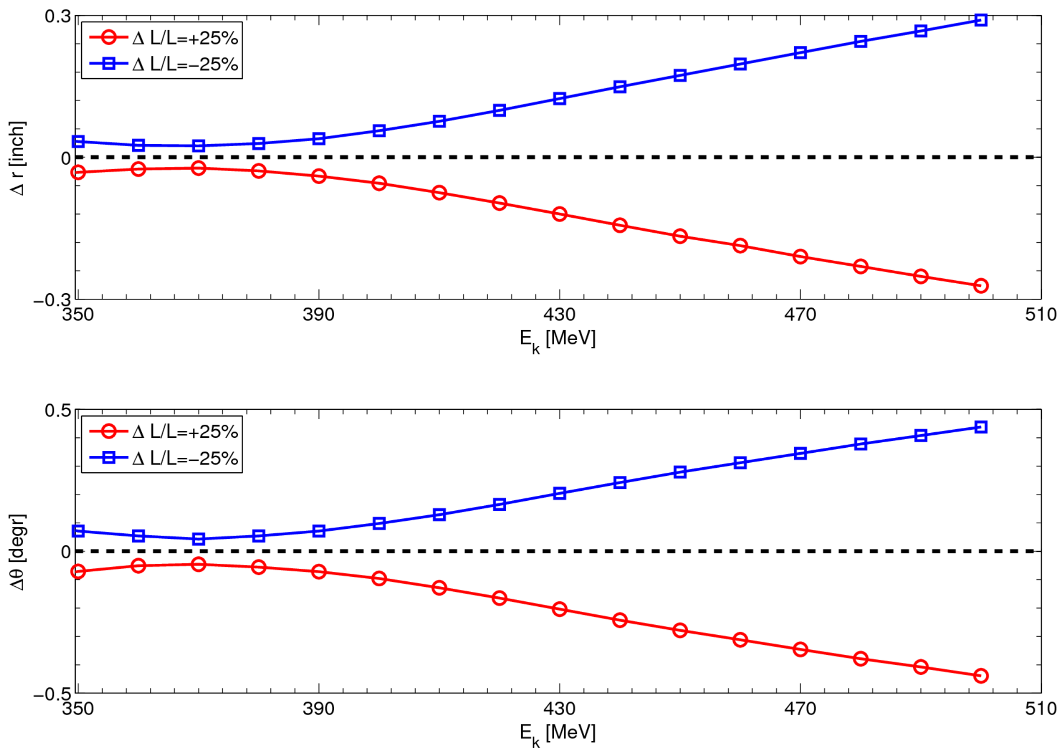


Figure 3: *Shift in the $r$ and $\theta$ coordinates of extraction probe due to its setting of $L$ deviated from the theoretical value by $\pm 25\%$ while $R$ remains unchanged. These were calculated with the formulas given in the context.*