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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.

# 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  $-5^\circ$  to make room for the longitudinal polarization solenoids, but the combination magnet was not moved or changed on purpose since day one [5]. This  $-5^\circ$  rotation means that the BL4 axis was at  $5^\circ$  to the right of the combination magnet axis [6] [7], looking downstream. 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.

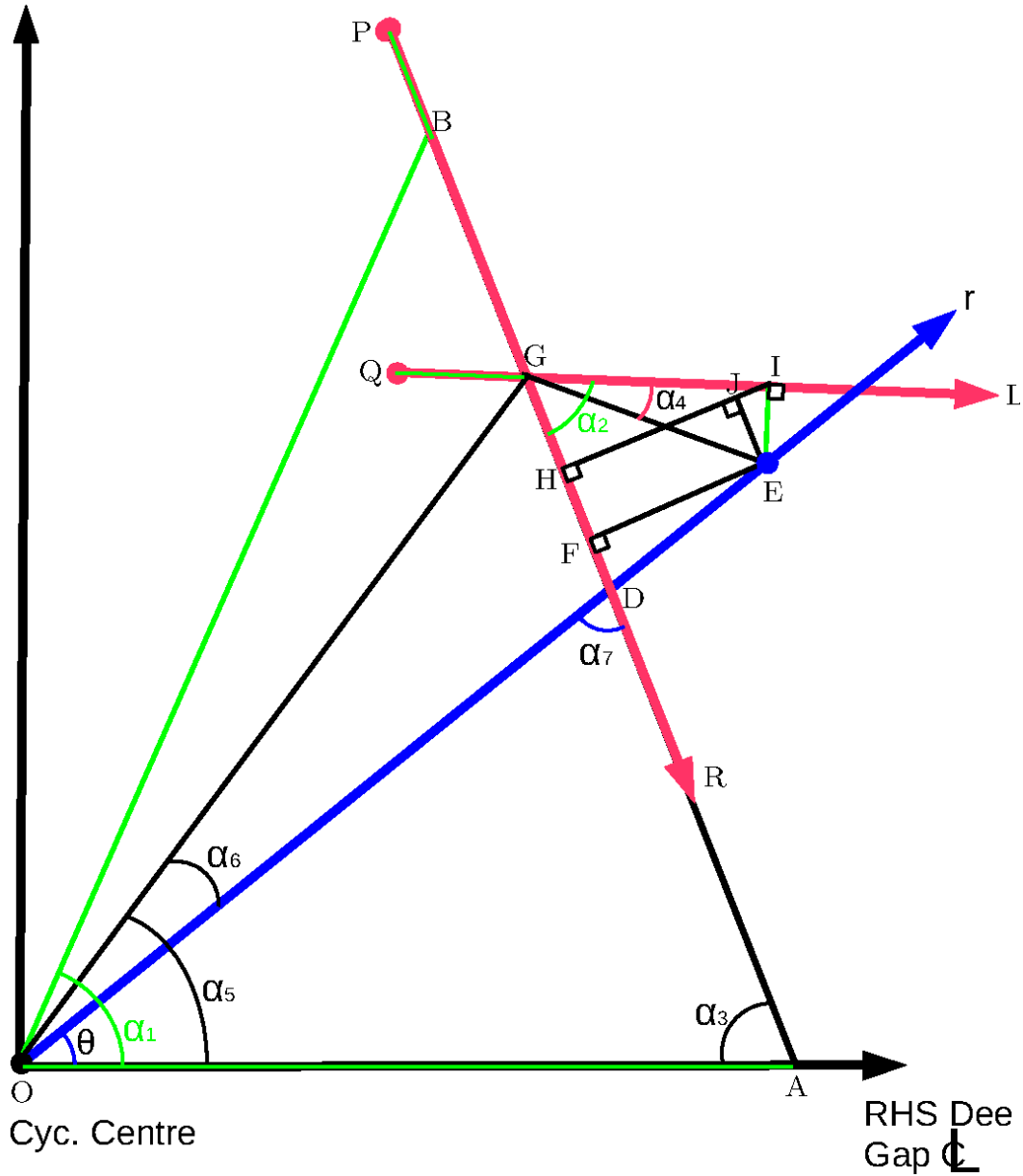


Figure 1: Schematic diagram showing geometrical correlation between the old BL4 probe's coordinates  $(R, L)$  and the cyclotron polar coordinates  $(r, \theta)$ . The points  $P$  and  $Q$  denote the pivots of probe arms along the  $R$  and  $L$  paths respectively, in other words, they are the origins of  $R$  and  $L$  axes. Note that  $r = \overline{OE}$ ,  $R = \overline{PG}$  and  $L = \overline{QI}$ . **Should be stressed that the line segments and angles in green namely  $\overline{OA}$ ,  $\overline{OB}$ ,  $\overline{PB}$ ,  $\overline{QG}$ ,  $\overline{EI}$ , as well as  $\alpha_1$  and  $\alpha_2$  are the parameters that must be determined by actual measurements, as these parameters depend on the design of the extraction probe.**

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

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

in which

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

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

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

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

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

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; 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.

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

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

in which

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

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

$$\begin{aligned} \overline{BA} &= \sqrt{\overline{OA}^2 + \overline{OB}^2 - 2\overline{OA}\overline{OB} \cos \alpha_1} , \\ \overline{GE} &= \sqrt{\overline{GI}^2 + \overline{EI}^2} , \quad \overline{GI} = \overline{QI} - \overline{QG} = L - \overline{QG} , \\ \alpha_3 &= \arccos \left( \frac{\overline{OA}^2 + \overline{BA}^2 - \overline{OB}^2}{2\overline{OA}\overline{BA}} \right) , \\ \alpha_5 &= \arccos \left( \frac{\overline{OG}^2 + \overline{OA}^2 - \overline{AG}^2}{2\overline{OG}\overline{OA}} \right) , \\ \alpha_4 &= \begin{cases} \arctan(\overline{EI}/\overline{GI}) & , \text{ if } \overline{EI} \neq 0 \text{ or } \overline{GI} \neq 0 \\ 0 & , \text{ otherwise} \end{cases} , \\ \angle EGO &= 180^\circ - \alpha_5 - \alpha_3 + \alpha_2 - \alpha_4 , \\ \alpha_6 &= \arccos \left( \frac{\overline{OG}^2 + r^2 - \overline{GE}^2}{2\overline{OG}r} \right) . \end{aligned}$$

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  $-5^\circ$  (in the old beamline 4 case) and at  $0^\circ$  (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  $\theta = 0^\circ$ , is directing to the right-hand side Dee gap center line while  $+y$  axis is  $90^\circ$  counterclockwise rotation from  $+x$  axis.

p-beam energy (MeV)	$-5^\circ$ exit		$0^\circ$ 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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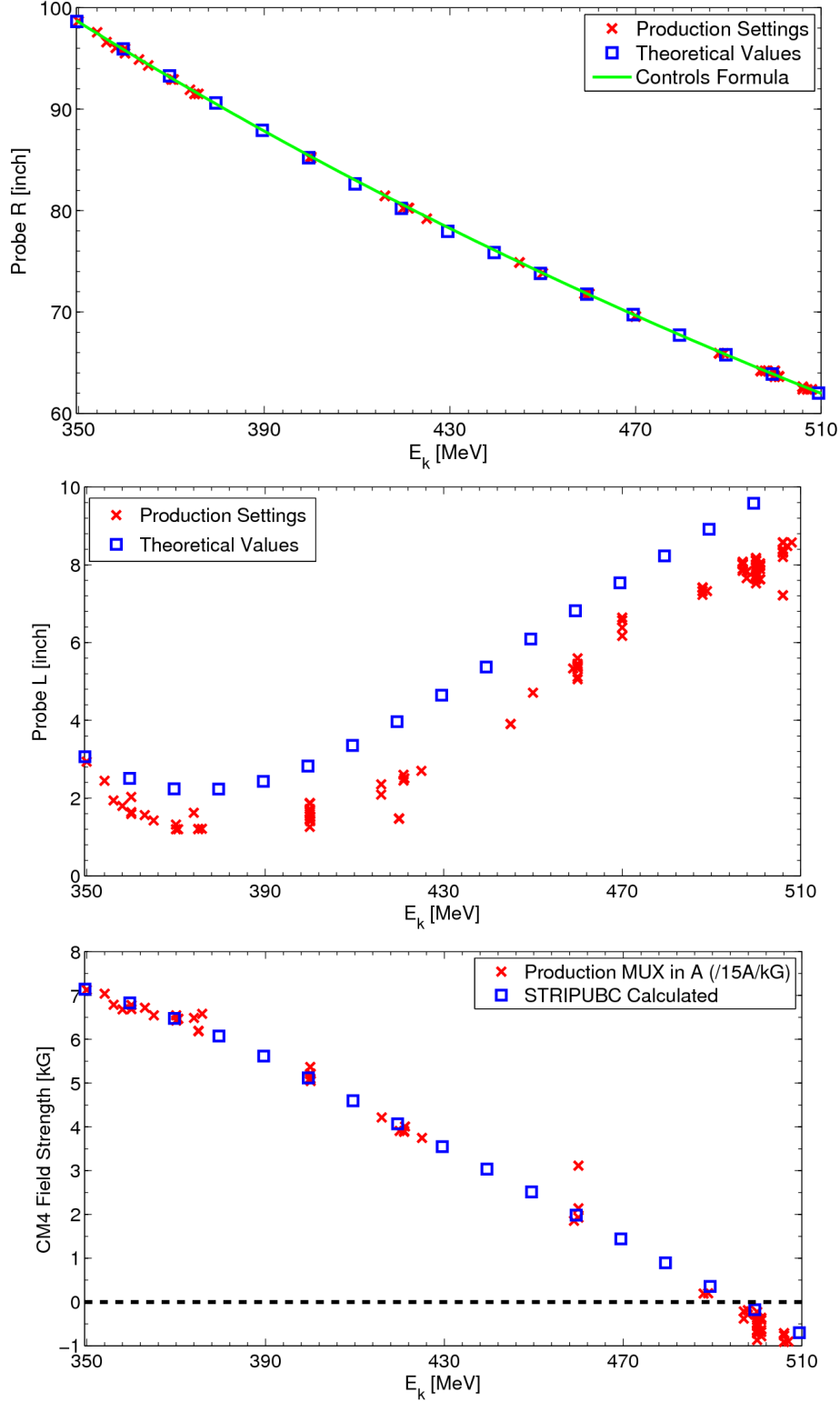


Figure 2: The old BL4 extraction probe's coordinates in R (Top) and L (Middle) and the combination magnet excitation (Bottom) vs. the energy of beam extracted. Note that the "Controls Formula" means this is the result calculated with a formula coded in the control's software [9] for the BL4, namely,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



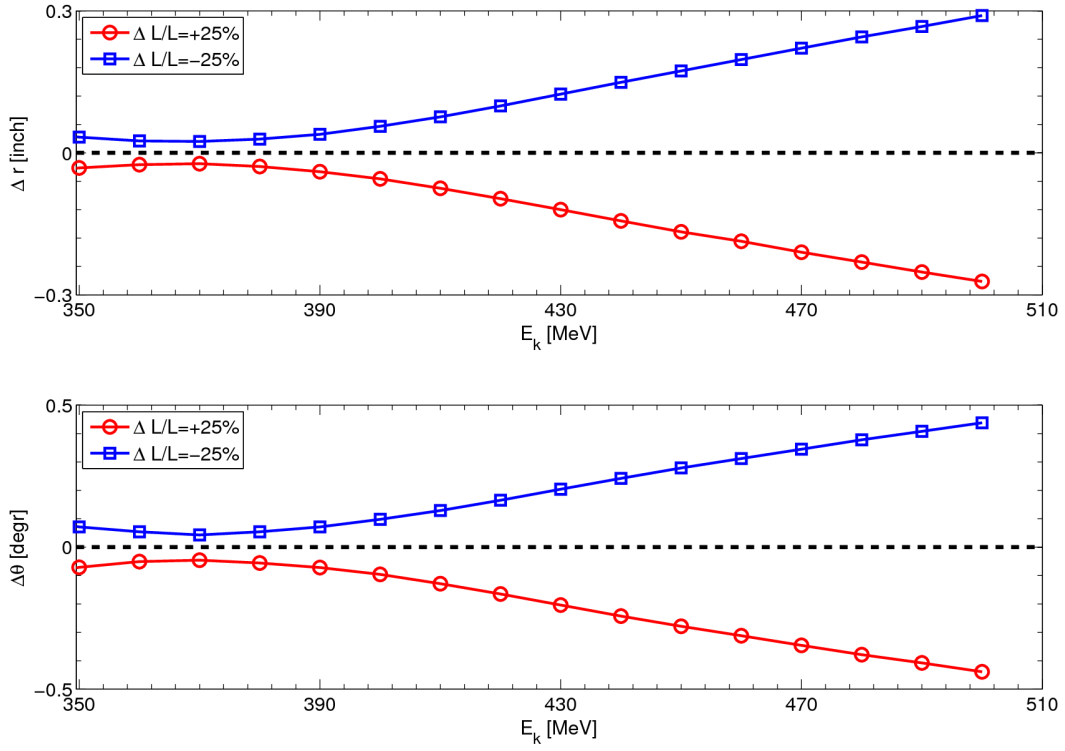


Figure 3: Shift in the  $r$  and  $\theta$  coordinates of extraction probe due to its setting of  $L$  deviated from the theoretical value by  $\pm 25\%$  while  $R$  remains unchanged. These were calculated with the formulas given in the context.