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Improved Beam Line 1A (BL1A) Optics
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History of Changes

Release number	Date	Description of changes	Author
01	2022-04-11	Draft 1 for review.	Y.-N. Rao
	2022-12-12	1. With respect to reviewers' comments, I added up one column in Table 1 under "Section 7 Elements List" to indicate the types of quads and steerers. Also, added up statements about inclusion of target scattering in the optics model. 2. As per physicist request, I added up a short paragraph and one figure under "Section 6 Improved Optics" to describe the minimum beam size that can be possibly created at T1 and T2.	

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1 Abstract

In view of the current configuration and operation status of BL1A, potential improvements are proposed to the beamline optics. These include: (1) replace the last triplet with 2 doublets to mitigate the quadrupole magnet's overheating issue and offer more flexibility for the beam match with TNF; (2) add up 2 quads to enable vertical focusing improvement through 1U septum magnet and facilitate beam match with T1 target, and (3) add up necessary diagnostics for measurements of the beam position and profile. Above all, the misalignment issue in the T2 area must be addressed with high priority in any circumstances. With these improvements in place, we expect to make the beamline easier to tune and diagnose aiming it towards the goal of stable and reliable operation with intensity up to 150 µA.

2 Current Status and Potential Improvements

The beamline 1A (BL1A) has been running for nearly 50 years. It routinely delivered high intensity proton beam of 100−150 µA within energy range of 480−500 MeV for decades from the cyclotron to the Meson Hall users [1, 2]. However, the present maximum operational beam current is only about 100 µA [3]. This delivery level is to a great extent limited by the beam losses occurring around the T2 collimators. The misalignment in the T2 area [4], including the T2 protect monitor and the T2 target as well as the collimators A and B, increases the losses, causing a large number of beam trips on the spill monitors and excessive radiation around. In any circumstances the misalignment issues must be addressed with high priority. Besides, the last quadrupole triplet 1AQ14,15,16 suffers from overheating (due to corrosion and clogging of the cooling channels in the magnet coils), especially in Q15 as it has the highest excitation, requiring frequent flushes. During the past 6-year's production runs, the lowest setting of Q15 was 778 A. This occurred only when both T2 and T1 were using a thin target of 12 mm (Beryllium). The highest setting of Q15 reached 850 A when a thicker target of 50 mm was used at T2. To alleviate the issue, one can't simply turn off Q15 and then run Q14,16 as a doublet to get beam into TNF, even if we reverse Q16 polarity. That would bring significantly more losses and higher temperature rise on the collimators. Currently, Q15 works at much higher excitation (>60%) than the other two. One of the remedies for this issue is to employ a longer quad for the Q15 (e.g. double the length). Alternative and more optimal configuration is to replace the triplet with two doublets. This would equalize the current density among the middle 2 magnets, and also bring more flexibility for matching the beam size onto TNF.

Another issue of BL1A optics is that the front-end two quadrupole triplets (1VQ1,2,3 and 1VQ4,5,6) are shared and bounded by 1A and 1U two lines when they are running in parallel; the two triplets are not freely tunable parameters. Moreover, the 1U optics has very little tunability for adjustment of the spot size at UCN target because it has no enough quads of its own. As a result, we'll have to: (1) establish a new tune for the triplet 1VQ4,5,6, plus (2) interlock the 1U quad 1UQ1 operating range, to allow for a desired large enough beam spot created at the UCN target with the present optics layout. This means that for the BL1A we are left with only 2 independent knobs namely 1AQ7,Q8 that we could use for adjusting the spot size at T1 as per user's requirements. But, these 2 knobs do not necessarily work out because they are too close to each other, far from being orthogonal in the phase space. In addition, from 1VQ6 to 1AQ7, it's a very long drift of 16 meter. Thus, the beam size blows up vertically (see Fig. 1). The beam halo becomes very broad, very likely getting scraped on 1U septum magnet which has an aperture reduction from regular 4 inch to 2 inch, causing beam trips on the spill monitor(s) and machine down time. A potential improvement to this issue would be to add up 2 quads in between to augment focusing and enable greater flexibility for the beam match with T1 target.

There are other aspects of BL1A that are non-optimal in terms of the beam optics. First, the original design was based on an incorrect understanding of the cyclotron beam. This arose from an error in the original beam tracking code (STRIPUBC) that tracked from the stripper to the combination magnet [5]. Second, the beamline could be made doubly achromatic with respect to the circulating beam, i.e. cancelling the "foil dispersion" as shown in Fig. 1. This would make the beam position insensitive to small fluctuations in the stripper position, obviating ongoing steering corrections as the foil heats and ages. Nevertheless, under today's condition this idea seems to be impractical because it would require moving the front-end dipole magnet 1VB1 further downstream by $\sim$1.2 m from its present location to configure a suitable FODO lattice to cancel the foil dispersion. This implies that all the downstream facilities would have to shift from their present locations, which is not practical.

The beam instrumentation is another big concern of BL1A; currently we are missing stable and reliable beam position monitors (BPM) and beam profile monitors in 1A. The reasonable number of BPM's for the beamline would be 7, while we have recently installed only 3. Besides, we must develop a new type of wire scanner (WS) which is capable of measuring x and y profiles of the 480 MeV proton beam with intensity varying from 10 nA up to 150 µA with sufficiently good signal-to-noise ratio. The measurement of low intensity beam ($<$100 nA) is essential for routine check of the beamline tune, especially when the machine just starts up from shutdown or maintenance. Whereas the measurement for high intensity beam ($>$10 µA) is necessary for accurate characterization of the beam property under realistic operational condition of the machine.

3 Objective

This document describes improvements we make to the BL1A optics in terms of experimental and beam physics requirements, beamline layout and element coordinates, as

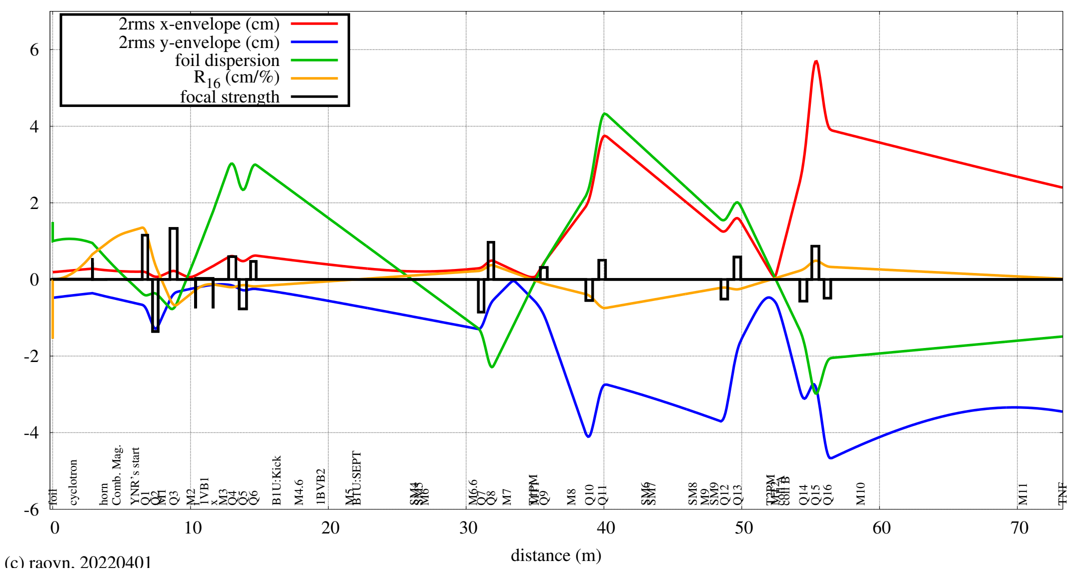

Figure 1: *Current standard tune of BL1A, showing the beam envelope (2rms) and dispersion starting from the stripper foil throughout the beamline. Here the "foil dispersion" in green is calculated from* $(R_{11}D + R_{12}D' + R_{16})/D$*, where* $D = -3.1$ *m and* $D' = -0.30$ *rad=*-3.0 *mrad/% are the cyclotron positional and angular dispersions at the foil location,* R_{11} *(dimensionless) and* R_{12} *(in cm/mrad) are the R-matrix elements. Thus, the green curve reveals a magnification of beam position shift due to average energy change of the beam at foil caused by for example the foil heating and curling. The transverse scattering, longitudinal energy loss and straggling due to traversal of T1 and T2 are included in the calculation; they are 12 mm and 50 mm long Beryllium targets respectively. Hereinafter the same.*

well as element specifications.

4 Related Documents

The following documents are the input to this design note:

- **Document-187515**: BL1A Configuration Optimization – Report of the Working Group [3].
- **TRI-BN-22-05**: Current Status of Beamline 1A Optics [4].

5 Requirements, Constraints and Assumptions [3]

- BL1A should transport proton beam with intensity up to 150 µA and energy range from 480 to 500 MeV.
- The proton beam is pulled out of the cyclotron extraction port #1 down to BL1A that branches off to 2 legs: BL1B and BL1U. The existing experimental facilities should stay where they are; these include the BL1B, BL1U and UCN facility, the T1 and T2 targets and meson channels, the 500 MeV IPF, as well as the TNF. This means that the whole geometrical layout of BL1A should remain unaltered from what it is now.
- No additional experimental facilities are recommended to build in the Meson Hall.
- Any implementation of modifications to the current configuration of BL1A should not need to require a multi-year shutdown of BL1A.
- The beam envelopes described in this design note are calculated for the beam energy of 480 MeV. This is based on the fact that the existing BL1A has been running at 480 MeV for over 10 years and will continue to run at 480 MeV.
- The initial condition of the beam at 480 MeV is [4]: $\alpha_x = -0.73$, $\beta_x = 3.50\,$m, ϵ_x=0.75 mm-mrad (4rms); $\alpha_y = 2.3$, $\beta_y = 24.7\,$m, ϵ_x=0.93 mm-mrad (4rms); $\Delta p/p = 6.4 \times 10^{-4}$ (2rms); $\eta = -1.55\,$m, $\eta' = -0.055$, where η and η' denote the beam positional and angular dispersions respectively. This refers to the condition of the beam dumped on the stripping foil when BL1A is alone taking all the beam of high energy, obtained from the `COMA` [6] simulation. The foil to be used is a carbon foil of typical thickness of 1.5 mg/cm^2. The scattering due to such a foil is 0.19 mrad (2rms) in both x and y planes.
- T1 and T2 are assumed to be 12 mm and 50 mm long Beryllium targets respectively. These are the typical thicknesses employed over the past 10 years or so.

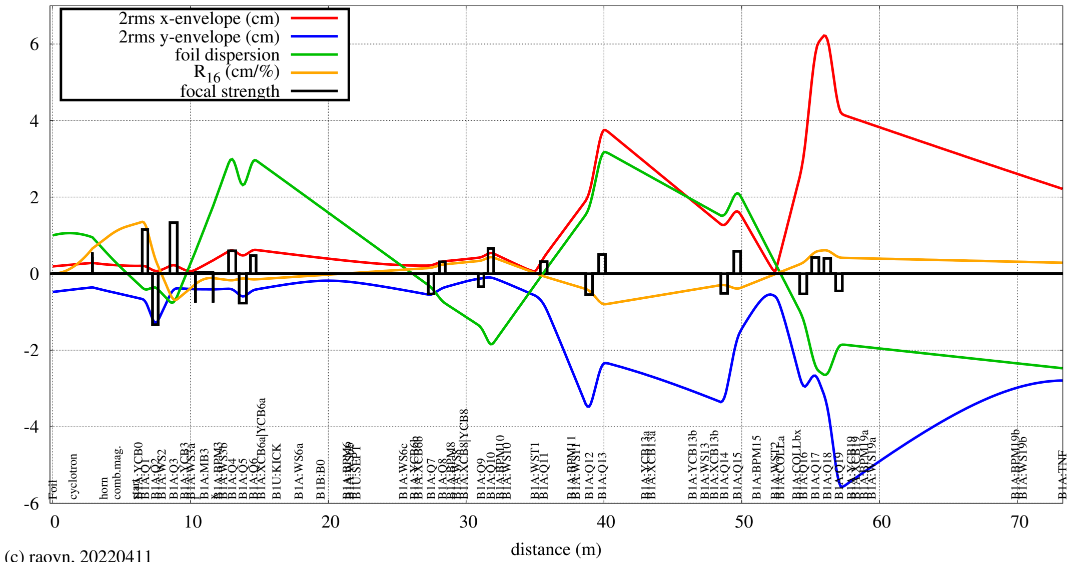

Figure 2: Improved BL1A optics, showing the beam envelope and dispersion.

6 Improved Optics

In view of the fore-mentioned issues, we've made improvements to the BL1A optics, subject to the constraints imposed. The result is shown in Fig. 2. In details:

- Replace the last triplet with 2 doublets, that is, add up one quadrupole magnet immediately after the existing Q16 and reverse Q16 from D to F so that Q16 assumes the same polarity as Q15. This way equalizes the excitation of Q15,16 and keeps them below 400 A, and also makes the final leg easier to tune.
- Add up one quadrupole doublet between the existing Q6 and Q7 to enable vertical focusing improvement through 1U septum magnet and facilitate beam match with T1 target.

New placement of BPM's and correctors is as follows.

- Add up a vertical steering magnet YCB0 in front of Q1 to replace the existing in-quad steerer SM0. This is in favour of polarity reversal to allow for two-way steering. The existing SM0 can't switch polarity. Although polarity change is obtainable by employing 4 trim power supplies to a single quad, it's not an optimal choice because the resulting field strength depends on particle's position, inducing deflection errors to the beam.
- Add up a pair of combined steering magnets (named B1A:XCB6a,YCB6a) between Q6 and B1V:Kicker to replace the function of the existing in-quad steerers 1VCBX,1VCBY. The in-quad steering is not as good as that of a real corrector as the field uniformity is poor, causing deflection errors to the beam. It's

worth mentioning that before the BL1U time, there were a pair of steerers (called 1VSM2,1VSM3) sitting in the area where the B1V:Kicker currently resides. So this new addition is sort of to restore them.

- Add up a BPM (B1A:BPM8) and a pair of steering magnet (B1A:XCB8/YCB8) in front of the existing quad Q7.
- Add up a pair of steering magnets (B1A:YCB19,XCB19) immediately after the last quad, to replace the function of the existing in-quad steerers SM10 and SM11A/B. The latter two do not have polarity reversal capability for two-way steering.
- Remove the T1 collimator since it's no longer used, and put a BPM there (B1A:BPM11). This monitor, along with the upstream B1A:BPM10, can determine the position and angle of beam passing through T1.
- Remove the ion chamber 1AT2ION, and place a BPM (B1A:BPM15) in front of T2 target.
- Add a BPM (BL1:BPM19a) in front of B1A:WS19a (wire scanner), and another one (B1A:BPM19b) in front of B1A:WS19b (wire scanner), to determine the position and angle of beam into TNF.

Placement of wire scanners for imaging the foil is:

- B1A:WS2 is located to image the horizontal position of beam at foil, where the R-matrix elements R_{12} and R_{16} are close to zero. See Fig. 3
- B1A:WS6b is placed to image the vertical position of beam at foil, where the R-matrix element R_{34} is close to zero. See Fig. 4.
- B1A:WS6c is placed to image the vertical angle of beam out of foil, where the R-matrix element R_{33} is close to zero. See Fig. 4.

With the improved lattice, a minimum spot size that can be possibly created at T1 and T2 is about 1.0 mm by 1.0 mm (2rms), shown in Fig. 5. This is achievable by making an exact π section between T1 and T2; as a consequence, whatever beam size obtained at T1 will be obtained at T2. Using the 4 matching quads B1A:Q7 $-$ B1A:Q10, one should have enough flexibility to vary the beam size at T1 within certain range.

7 Elements List

The table 1 lists, in sequence, the mid-point coordinates of magnetic elements (dipole, quadrupole and corrector) and diagnostic elements (BPM and WS). For the dipole magnet, the entrance, the mid-point and the exit along the reference trajectory are given.

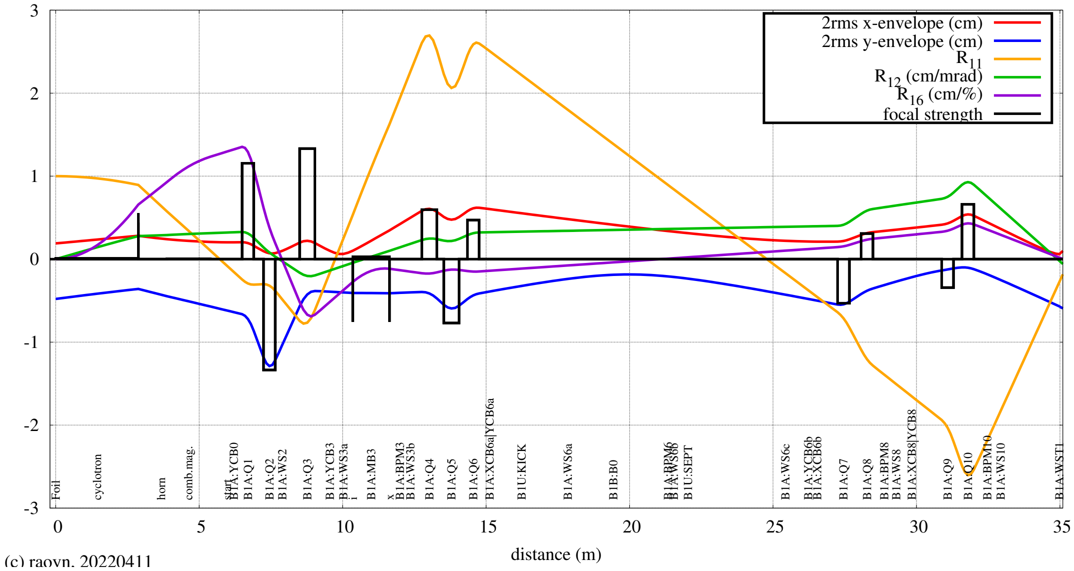

Figure 3: Improved BL1A beam envelope and horizontal R-matrix elements R_{11}, R_{12} and R_{16} up to T1. The profile monitor B1A:WS2 is placed to image the horizontal position of beam at foil.

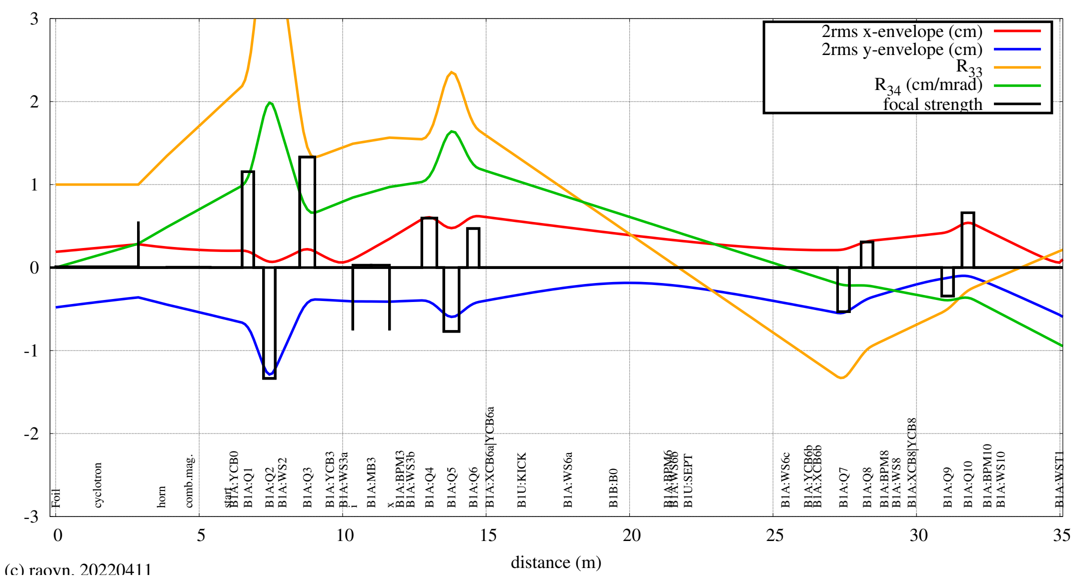

Figure 4: Improved BL1A beam envelope and vertical R-matrix elements R_{33} and R_{34} up to T1. The profile monitors B1A:WS6b and B1A:WS6c are placed to image the vertical position and angle of beam out of foil.

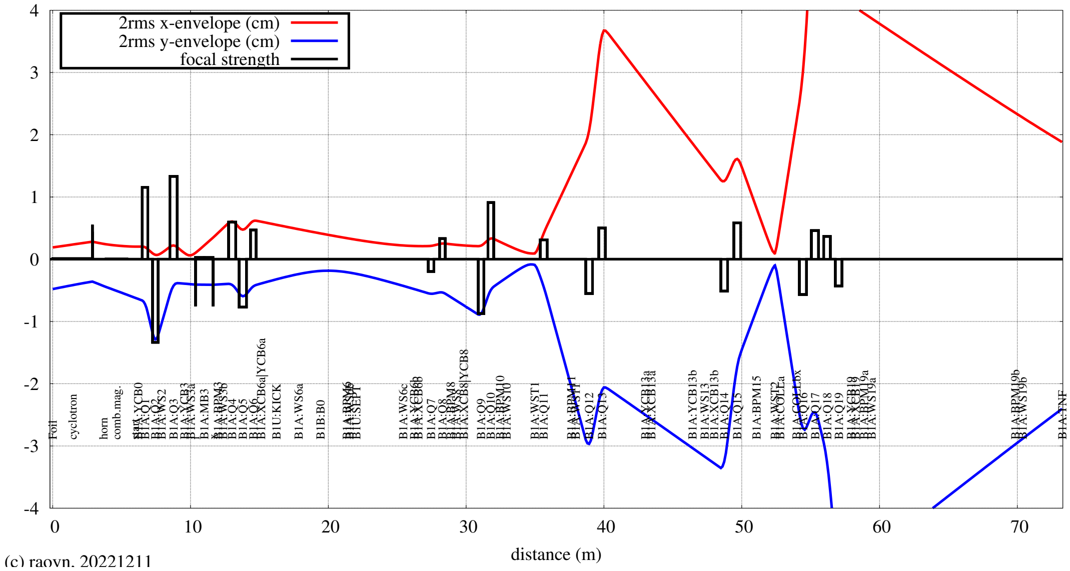

Figure 5: Envelope plot showing a minimum spot size that can be possibly created at T1 and T2 is about 1.0 mm by 1.0 mm (2rms).

The 2nd column is the reference trajectory length in meter, measured from the start-point which sits at 26.891 inch downstream from the combination magnet cross-over point on its exiting axis. The x-y-z frame is a Cartesian system where the origin is at the start-point, $+z$ axis points to the beam moving direction in line with the combination magnet exiting axis, $+x$ axis points to the right (looking downstream), and $+y$ axis points downward. The y coordinate of the reference trajectory is constantly zero as it falls in the cyclotron's median plane. The x-y-z frame is right-handed. Note that the first column gives the element names complying with the TRIUMF naming convention for EPICS, while the 2nd to the last column indicates whether the device is a new addition and/or what its present name is under Vax. The last column indicates the proposed types of magnets. All the quadrupole magnets are the TRIUMF existing types. Besides, it's worthwhile to mention that, wherever dictated, the x/y combined steering magnet is preferred for saving space. The B1A:YCB0 can be a modified KEK vertical steerer which has shorter insertion length, while the 4″ steerer is the TRIUMF standard type.

Table 1 Coordinates of Magnetic and Diagnostic Elements

Element EPICS Name	S [m]	X [m]	Z [m]	New Addition? and/or Vax Name	Magnet Type
start	0.000000	0.000000	0.000000		
B1A:YCB0	0.240000	0.000000	0.240000	Yes	mod. KEK
B1A:Q1	0.731468	0.000000	0.731468	1VQ1/1VSM0	4Q14/8
B1A:Q2	1.479169	0.000000	1.479168	1VQ2	4Q14/8

B1A:WS2	1.933169	0.000000	1.933168	Yes	1VM1	
B1A:Q3	2.799968	0.000000	2.799968		1VQ3	4Q19/8
B1A:YCB3	3.588167	0.000000	3.588169		1VSM1	4" steer.
B1A:WS3a	4.054866	0.000000	4.054869	Yes	1VM2	
i	4.388168	0.000000	4.388170			
B1A:MB3	5.026337	-0.054997	5.023170		1VB1	
x	5.664510	-0.218351	5.639258			
B1A:BPM3	6.029601	-0.342020	5.982763		1VBPM3	
B1A:WS3b	6.394691	-0.465689	6.326268	Yes	1VM3	
B1A:Q4	7.054457	-0.689177	6.947029		1VQ4	4Q19/8
B1A:Q5	7.824076	-0.949876	7.671150		1VQ5	4Q19/8
B1A:Q6	8.586075	-1.207994	8.388101		1VQ6	4Q14/8
B1A:XCB6a	9.154124	-1.400414	8.922568	Yes		x/y comb.
B1A:YCB6a	9.154124	-1.400414	8.922568	Yes		x/y comb.
B1V:KICK	10.268973	-1.778057	9.971511			
B1A:WS6a	11.878545	-2.323281	11.485931	Yes	1VM4.6	
B1B:B0	13.464561	-2.860528	12.978195			
B1A:BPM6	15.373960	-3.507315	14.774717		1AM4.7	
B1A:WS6b	15.573959	-3.575062	14.962894	Yes	1AM5	
B1U:SEPT	16.070564	-3.743280	15.430137			
B1A:WS6c	19.461267	-4.891836	18.620363	Yes		
B1A:YCB6b	20.259079	-5.162084	19.371004		1ASM4	4" steer.
B1A:XCB6b	20.573406	-5.268558	19.666746		1ASM5	4" steer.
B1A:Q7	21.488379	-5.578496	20.527626	Yes		4Q14/8
B1A:Q8	22.308384	-5.856261	21.299145	Yes		4Q14/8
B1A:BPM8	22.908382	-6.059505	21.863670	Yes		
B1A:WS8	23.328382	-6.201775	22.258841	Yes	1AM6.6	
B1A:XCB8	23.868383	-6.384693	22.766918	Yes		x/y comb.
B1A:YCB8	23.868383	-6.384693	22.766918	Yes		x/y comb.
B1A:Q9	25.116840	-6.807590	23.941559		1AQ7	4Q14/8
B1A:Q10	25.824867	-7.047424	24.607723		1AQ8	4Q14/8
B1A:BPM10	26.499863	-7.276073	25.242817		1AM6.9	
B1A:WS10	26.967855	-7.434602	25.683147	Yes	1AM7	
B1A:WST1	29.009390	-8.126143	27.603973	Yes	1AMT1	
B1A:Q11	29.660263	-8.346619	28.216370		1AQ9	8QN16M/9
B1A:BPM11	31.659321	-9.023768	30.097246	Yes		
B1A:WS11	31.992304	-9.136563	30.410547	Yes	1AM8	
B1A:Q12	32.957500	-9.463511	31.318689		1AQ10	8QN16M/9
B1A:Q13	33.897305	-9.781856	32.202930		1AQ11	8QN16M/9
B1A:YCB13a	37.037273	-10.845475	35.157261		1ASM6	4" steer.
B1A:XCB13a	37.469067	-10.991742	35.563538		1ASM7	4" steer.
B1A:YCB13b	40.461567	-12.005406	38.379120		1ASM8	4" steer.

B1A:WS13	41.347382	-12.305468	39.212578	Yes	1AM9	
B1A:XCB13b	42.028397	-12.536161	39.853355		1ASM9	4" steer.
B1A:Q14	42.760242	-12.784062	40.541927		1AQ12	8QN16M/9
B1A:Q15	43.704796	-13.104020	41.430649		1AQ13	8QN16M/9
B1A:BPM15	45.101814	-13.577236	42.745049	Yes		
B1A:WST2	46.441677	-14.031096	44.005676	Yes	1AMT2	
B1A:COLLa	46.829021	-14.162305	44.370129			
B1A:COLLbx	48.017830	-14.565008	45.488674			
B1A:Q16	48.496658	-14.727209	45.939205	Yes	1AQ14/SM10	8QN18M/9
B1A:Q17	49.369785	-15.022968	46.760708	Yes	1AQ15	8QN18M/9
B1A:Q18	50.242908	-15.318727	47.582211	Yes	1AQ16/SM11	8QN16M/9
B1A:Q19	51.086914	-15.604622	48.376308	Yes		8QN16M/9
B1A:YCB19	51.968964	-15.903406	49.206203	Yes		x/y comb.
B1A:XCB19	52.308964	-16.018578	49.526104	Yes		x/y comb.
B1A:BPM19a	52.908962	-16.221817	50.090633	Yes		
B1A:WS19a	53.448963	-16.404734	50.598705	Yes	1AM10	
B1A:BPM19b	63.880184	-19.938204	60.413334	Yes		
B1A:WS19b	64.420181	-20.121120	60.921406	Yes	1AM11	
B1A:TNF	67.302994	-21.097673	63.633884			

8 Summary

We proposed potential improvements to the BL1A optics, accommodating all the known requirements and constraints. These include: (1) replace the last triplet with 2 doublets to mitigate the quadrupole magnet's overheating issue and offer more flexibility for the beam match onto TNF; (2) add up 2 quads to enable vertical focusing improvement through 1U septum magnet and facilitate beam match with T1 target, and (3) add up necessary diagnostics for measurements of the beam position and profile. Above all, the misalignment issue in the T2 area must be addressed with high priority in any circumstances. With these improvements in place, we expect to make the beamline operation more stable and reliable with intensity up to 150 µA.

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