ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-WEP036

STUDY OF NON-DESTRUCTIVE BPM-BASED ENERGY MEASUREMENT OF THE CANADIAN LIGHT SOURCE LINAC

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Abstract

There is a plan in the Canadian Light Source (CLS) to replace the current Linac with a new one from Research Instruments GmbH in mid-2024. The first straight section of LTB (Linac-To-Booster) was upgraded to have two BPMs (Beam Position Monitors) with a 4.75 m drift between them and two phosphor screens were replaced by YAG screens. A new BPM and a YAG-based screen station upgraded the following 90-degree achromat beamline. These upgrades help us to measure the current and future Linac beam parameters, including the beam twiss parameters, energy, and energy spread. In this paper, we discussed how we could use these three BPMs for non-destructive energy measurement, which will be a part of the active energy correction system.

INTRODUCTION

Canadian Light Source's current electron linear accelerator will be replaced with a new one by Research Instruments GmbH in mid-2024 [1,2]. As part of the project, the beam diagnostic systems in the LTB were upgraded. Figure 1 shows the layout of LTB and where the current diagnostic components were upgraded or new components added. A new BPM, BPM2, added by pairing with the BPM1, measures the transversal position and momentum of the electron beam in the BPM2 location. There is a long drift between these two BPMs and one Steerer (ST0003-05), just 26.22 cm before that, and its effect is negligible compared to a pure drift as calculated. VSC0003-01 and VSC0003-03 phosphor screens were replaced by one inch round YAG screens, and the camera was upgraded to a digital one. This helps us to measure twiss parameters. Also, they can be used to calibrate BPMs. A new VSC0003-06 screen was installed in the achromat beamline to measure energy and energy spread destructively and be used as a reference to calibrate the BPM3. An online non-destructive method for the energy measurement is required for the energy monitoring by operators and potentially to use in an active energy correction system, which uses a script which implement a negative feedback system to change the phase of the Linac accelerating section to keep the energy constant. For this purpose, a new BPM, SLM0003-03 (BPM3), was installed in the achromat beamline just before the new screen station and after the slit. The slit will be upgraded, as part of the project, for the beam profile scanning and energy filtering. When we combine these three BPMs together, as we suggest, we can measure the energy non-destructively. The first two are to measure the transverse position and momentum of the beam just before entering the achromat beamline in the location of the BPM2. Then, using the transfer matrix between the BPM2 and the BPM3 and the location of the beam read by the BPM3, we can find the energy of the electron beam.

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TRANSFER MATRIX & NORMALIZED X

The position of the beam at BPM3, SLM0003-03, is a function of the beam energy and the beam position and momentum at the BPM2 location. Here we defined a new parameter, normalized horizontal position, or normalized x, which is just a function of energy. To calculate that, we should know the transversal position and momentum of the beam in the BPM2 location. We can measure x_1 and x_2 and Eq. (1) shows how we can calculate x_2' by knowing the drift length between them, which is 4.7518 m.

$$\begin{Bmatrix} x_2 \\ x_2' \end{Bmatrix} = \begin{Bmatrix} 1 & D \\ 0 & 1 \end{Bmatrix} \begin{Bmatrix} x_1 \\ x_1' \end{Bmatrix} \Rightarrow x_2' = (x_2 - x_1)/D \quad (1)$$

Equation (2) shows the position and momentum at the BPM3 location, knowing the transfer matrix and the position and momentum at the BPM2 location. We used a 3x3 transfer matrix which included the horizontal information and dispersion. Because of using linear elements, the vertical components are decoupled.

$$\begin{Bmatrix} x_3 \\ x_3' \\ \Delta p/p \end{Bmatrix} = M \begin{Bmatrix} x_2 \\ x_2' \\ \Delta p/p \end{Bmatrix} \quad (2)$$

Now we can define the normalized x which is equal to $\Delta p/p$ as you can see in Eq. (3) and it is a function of horizontal beam position in three BPMs, the drift length between BPM1 and BPM2 and the first row of the transfer matrix between the BPM2 and BPM3.

$$\begin{aligned} x_3 &= M_{11} * x_2 + M_{12} * x_2' + M_{13} * \Delta p/p = \\ &M_{11} * x_2 + M_{12} * (x_2 - x_1)/D + M_{13} * \Delta p/p \Rightarrow \\ x_n &\equiv [x_3 - M_{11} * x_2 - M_{12} * (x_2 - x_1)/D] / M_{13} = \Delta p/p \end{aligned} \quad (3)$$

The BPM2 to BPM3 transfer matrix can be calculated by knowing the elements between two BPMs.

$$M = M_{D4} * M_{QF2} * M_{D3} * M_B * M_{D2} * M_{QF1} * M_{D1} \quad (4)$$

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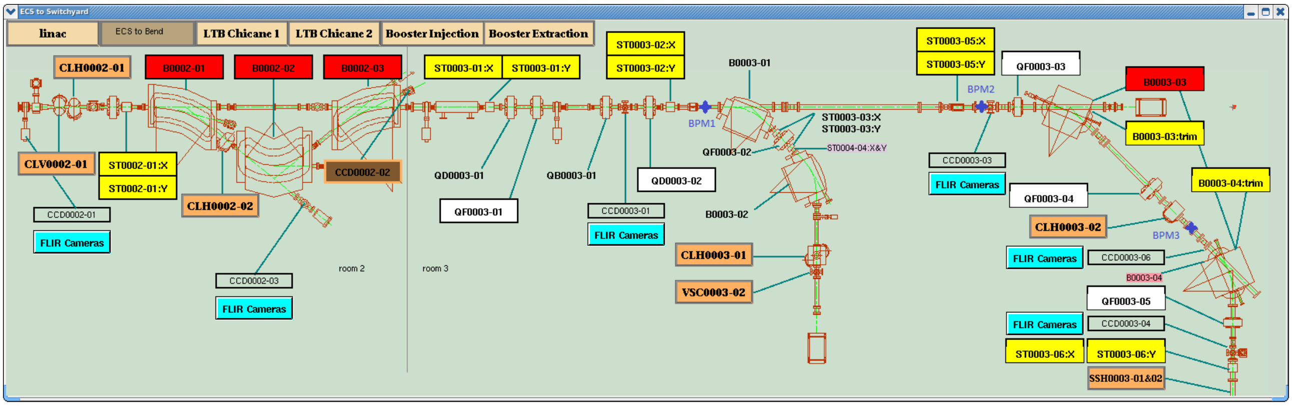

Figure 1: The LTB layout with BPMs positions, BPM1 (SLM0003-02), BPM2(SLM0003-01), BPM3(SLM0003-03) and screens (VSC0003-01, VSC0003-03, VSC0003-06).

M_{D1-4} is a drift transfer matrix and D_{1-4} = 0.6849, 0.45775, 1.54695, 0.7328 m is the drift length. M_B is a sector dipole transfer matrix, ϕ is the dipole angle and R is its radius. $\phi = 45^\circ$ and R = 850 mm in our case. $M_{QF1,2}$ is a focusing quadrupole transfer matrix, $\mu = \sqrt{k}$ which k is the quadrupole focusing strength and L is the quadrupole length. Both quadrupole length is 166.1 mm. $k = 0.2148I$ 1/m^2 [3] and the first and second quadrupole coil current is 9.14 A and 28.35 A, respectively. Equations (5)–(7) show the transfer matrix for a drift, sector dipole and a focusing quadrupole, respectively [4].

$$M_{D1-4} = \begin{Bmatrix} 1 & D_{1-4} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{Bmatrix} \quad (5)$$

$$M_B = \begin{Bmatrix} cos(\phi) & Rsin(\phi) & R(1-cos(\phi)) \\ -sin(\phi)/R & cos(\phi) & sin(\phi) \\ 0 & 0 & 1 \end{Bmatrix} \quad (6)$$

$$M_{QF} = \begin{Bmatrix} cos(\mu L) & sin(\mu L)/\mu & 0 \\ -\mu sin(\mu L) & cos(\mu L) & 0 \\ 0 & 0 & 1 \end{Bmatrix} \quad (7)$$

Now we can calculate the total transfer matrix, using the mentioned current parameters. It is easy to recalculate it or it is part of the script to calculate energy and to do the energy correction using different currents for quadrupoles. Equation (8) shows the BPM2-BPM3 transfer matrix when the achromat beamline middle quadrupole, QF0003-04, is ON and in its nominal value. It is also practical for offline measurement to turn this quadrupole off for a better energy and energy spread measurement resolution. Equation (9) shows the transfer matrix when this quadrupole is off.

$$M_{ON} = \begin{Bmatrix} -0.9643 & -0.2553\text{ m} & 0.8533\text{ m} \\ 0.1700\text{ (1/m)} & -0.9920 & -0.6720 \\ 0 & 0 & 1 \end{Bmatrix} \quad (8)$$

$$M_{OFF} = \begin{Bmatrix} -1.8485 & 0.1918\text{ m} & 1.9784\text{ m} \\ -0.9149\text{ (1/m)} & -0.4460 & 0.7071 \\ 0 & 0 & 1 \end{Bmatrix} \quad (9)$$

Now we can rewrite Eq. (3) using the M_{ON} transfer matrix, which shows how we can calculate the normalized x based on the current parameters.

$$x_n \equiv \frac{x_3 + 0.9643 * x_2 + 0.2553\text{ m} * \frac{(x_2 - x_1)}{4.7518\text{ m}}}{0.8533\text{ m}} = \Delta p/p \quad (10)$$

BPM CALIBRATION

We must calibrate BPMs and do alignment corrections based on the mechanical LTB coordinates survey [5] before implementing them in Eq. (10). We will start with the BPM2. As shown in Fig. 1, there is the VSC0003-03 screen, 294.7 mm after the BPM2. We use it as a reference since it was grided, and we can directly see the beam profile dimension and position. There is a positive axial offset of 1.62 mm for BPM2 compared to this screen, as measured mechanically during the LTB survey. We should consider the offset and the drift to add to the measured position with the BPM to find equivalent positions. We will use the BPM1 measured position to correct this drift to calculate x_2' using Eq. (1). Also, the small effect of the ST0003-05X steerer that was 262.2 mm before the BPM2 was calculated to correct the x_2' at the BPM2 location. Figure 2 shows the result. The scanning was done using the ST0003-02X steerer. We should also consider the negative axial offset of 0.835 mm for BPM2 compared to BPM1. Then, we can use the following equation for BPM1-3 to find the horizontal position based on the BPM x measurement.

$$\begin{cases} x_1 = 2.59x_{BPM1} + 4.46\text{ mm} \\ x_2 = 2.59x_{BPM2} + 3.62\text{ mm} \\ x_3 = 2.53x_{BPM3} - 11.53\text{ mm} \end{cases} \quad (11)$$

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We assumed BPM1 following the same calibration slope. Measurement of the VSC0003-01 screen behind the BPM1 confirms that roughly. Also, the beam goes through a very small horizontal spanning in the BPM1, and then a slight slope change is negligible. The result of the BPM3 calibration also confirms this assumption since all these three BPMs are similar.

Now, we should go to calibrate BPM3. For the BPM3, we used the data of the VSC0003-06 screen by scanning the ST0003-02X steerer and considered the drift and alignment between the screen and the BPM. The data was taken when the achromat beamline quadrupole was off for a better resolution. To correct the drift effect, we need to know the x_3'. For that, we are using Eq. (9). The negative axial offset of 0.644 mm for BPM3 compared to VSC0003-06 was also considered. Figure 3 shows the calibration result. It shows almost the same calibration factor of BPM1 and BPM2 but a negative polarity compared to them, Eq. (11).

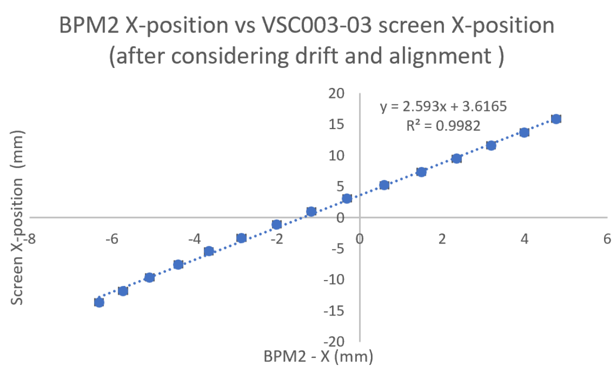

Figure 2: BPM2 calibration result.

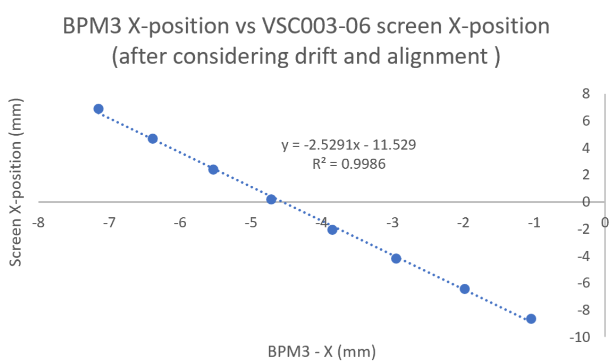

Figure 3: BPM3 calibration result.

ENERGY MEASUREMENT RESULT

Now, we have the tool to start energy measurement. First, we checked the model by scanning the ST0003-02X steerer without changing the beam energy. The VSC0003-06 shows horizontal displacement of the beam profile, which we know comes from the beam's horizontal position and momentum on the BPM2 location, not from the energy variation. Measuring BPM1-3 horizontal data and using Eqs. (10) and (11), we see the result in Fig. 4. Energy variation is about 0.07 %, below 0.1 %, which is the pulse-to-pulse energy jittering of the current and the new Linac. The non-zero average energy is arbitrary and depends on how we select the nominal energy, which is about 250 MeV. It shows our model works well. Now, we can measure the energy by scanning the last accelerating structure phase. The last accelerating section is operating off-crest as a tool to correct the total beam energy of the Linac. Figure 5 shows the result. The energy changes linearly around the nominal phase (~ 110.3°), but we saw some non-linearity below ~ 104°. Although the energy correction script operates in the linear part, further study for non-linear behaviour could be helpful.

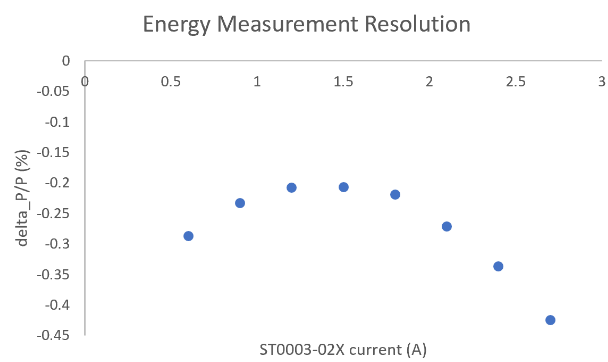

Figure 4: Energy measurement resolution, 0.07%.

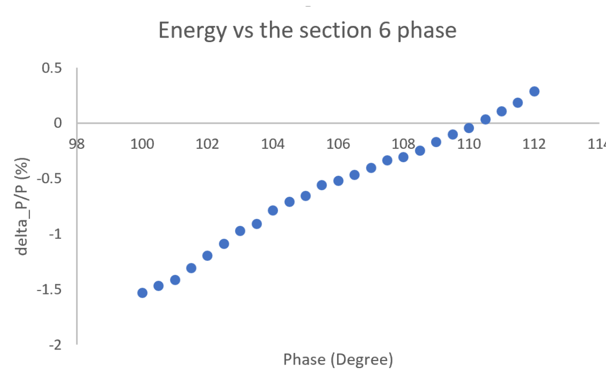

Figure 5: Energy measurement by scanning the last accelerating section phase.

CONCLUSION

The proposed BPM-based non-destructive energy measurement method shows a good resolution which is below the machine energy jittering. Based on this method, we prepared a script to measure and correct the Linac total energy. This script will be used for the new Linac, and operators can monitor the long-term operation of the Linac. Further non-linear studies will be helpful for more accurate energy measurements.

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