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BL1U Commissioning and Test Results

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Abstract: The note summarizes the results of BL1U commissioning and tests of Aug. 23 and Sept. 03, 2024, on which we achieved the final milestone of running BL1U and BL1A under kicking mode with full intensity of 40 μA down 1U and 80 μA down 1A.

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1 BL1U Tune

Fig. 1 shows the BL1U theoretical tune that has been demonstrated capable of running 1U and 1A under kicking mode with full intensity of 40 µA down 1U and 80 µA down 1A. The quads settings are: 1VQ1=311 A, 1VSM0=10.6 A, 1VQ2=358 A, 1VQ3=346 A; 1VQ4=155 A, 1VQ5=191 A, 1VQ6=115 A; 1UQ1=38 A and 1UQ2=0. The predicted beam spot size at UCN target is 11.2 mm (2rms) in x and 4.2 mm in y, which meets the UCN requirement. **All these quads are not supposed to be freely tuned except for a tweak purpose but the fine adjustment must be within ±2%. For interlock purpose, 1UQ2 must be off and 1UQ1 must not run between 45 A and 68 A in order to protect the BL1U end window and UCN target against overly dense beam.**

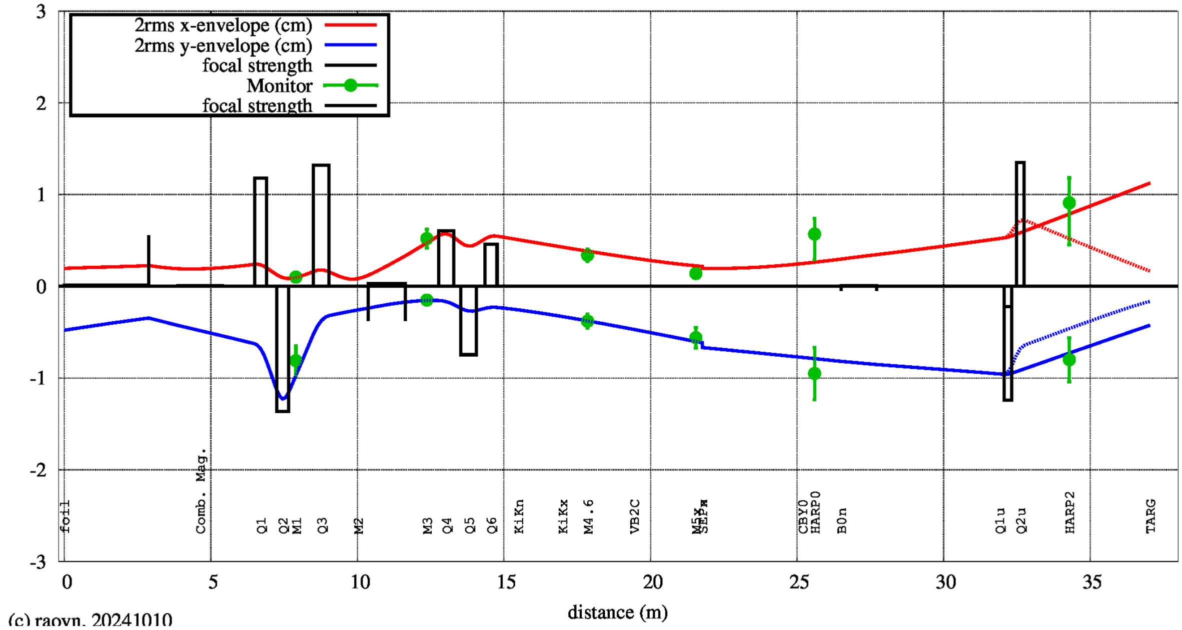

Figure 1: *BL1U theoretical tune which was demonstrated to run 1U and 1A under kicking mode with full intensity of 40 µA down 1U and 80 µA down 1A. The 2 dashed lines represent the envelope reduced by running the last doublet 1UQ1 and 1UQ2 at 200 A and 238 A respectively for target protect monitor scan purpose.*

2 Target Protect Monitor (TPM) Calibration

Since there is no total plate in B1U:TPM2, ratios to this plate cannot be used, the signal provided by the TPM needs to be calibrated to the proton beam current using other techniques. This was fulfilled by scanning a small beam spot through the TPM plates. The spot size is about 1.6 mm (2rms, half) in both x and y, predicted by the beamline optics calculation for which the last doublet 1UQ1 and 1UQ2 are set to 200 A and 238 A respectively (see Fig. 1).

The scans were taken under DC mode of kicker, during which a beam current of 2.2 µA at 10% duty cycle was delivered to BL1U. So the peak current was 22 µA, needed to be above 20 µA for achieving good enough signal to noise ratio for the BPM measurements.

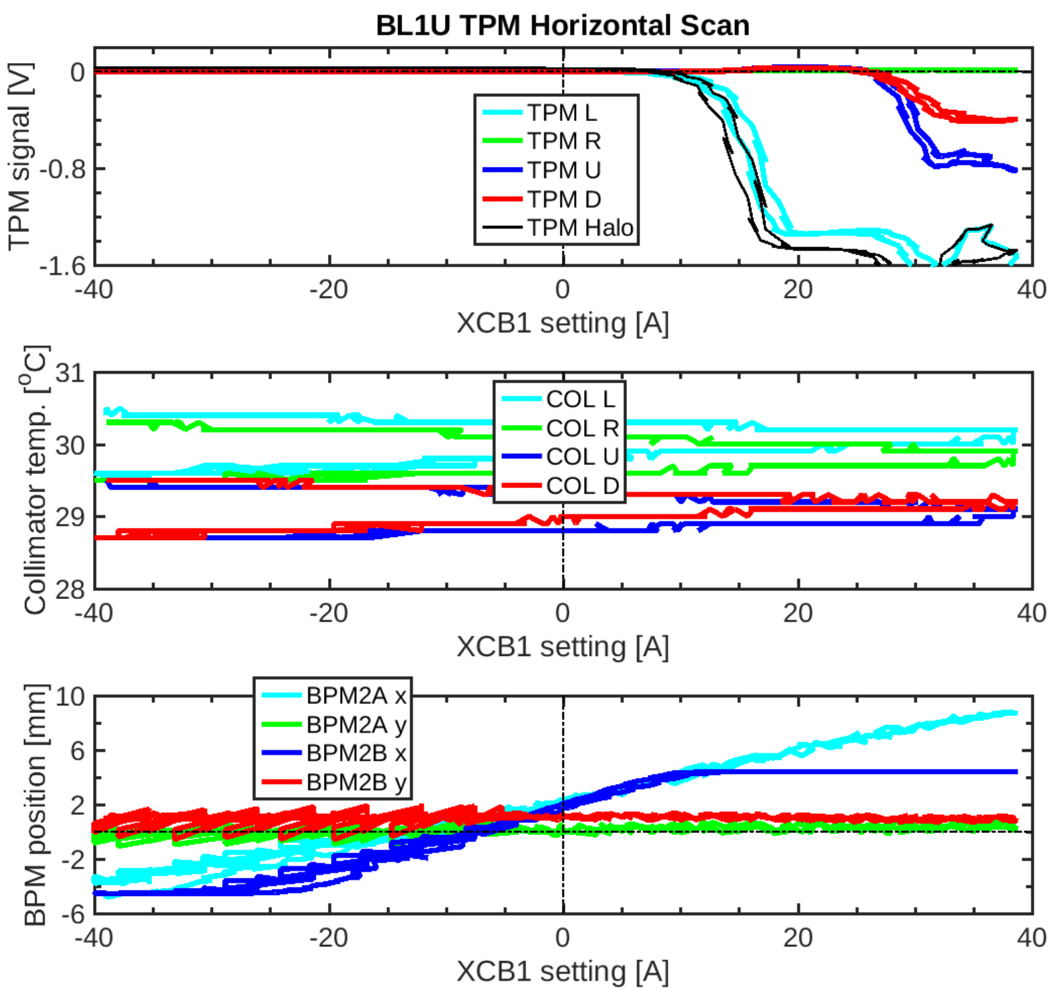

Figure 2: *TPM horizontal scan with steerer XCB1, showing the plate signals (Top), collimator temperatures (Middle) and the 2 BPM's measured beam positions (Bottom).*

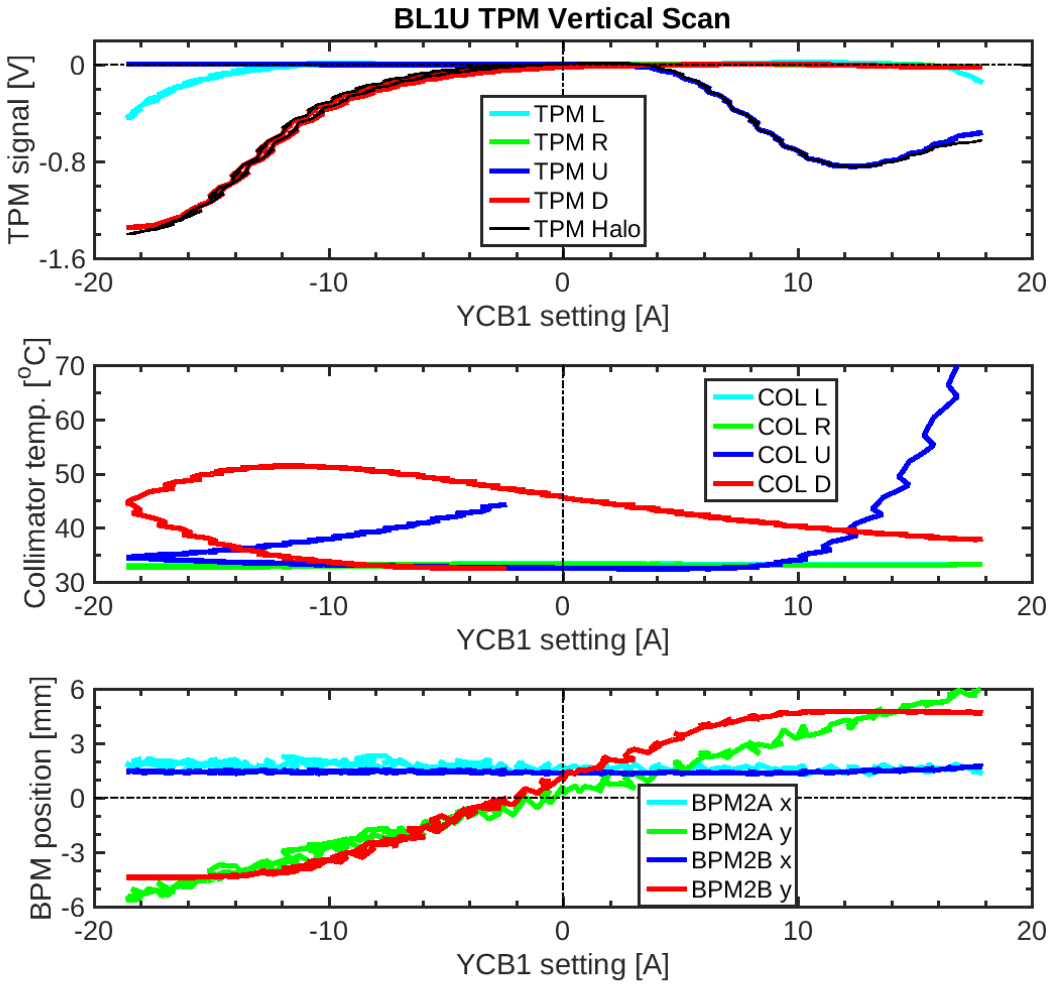

Figure 3: *TPM vertical scan with steerer YCB1, showing the plate signals (Top), collimator temperatures (Middle) and the 2 BPM's measured beam positions (Bottom).*

Fig. 2 and 3 show results of the horizontal and vertical scans respectively. Clearly, the left plate exhibits a flat-top maximum signal and a flat-bottom zero signal. The halo plate displays a similar picture. This suggests that the beam spot in the horizontal direction has been made small enough so that it can completely fall inside the Tantalum plate of 5 mm wide. The right plate barely displays any signal, as the TPM is misaligned to the right by 6 mm at least, looking downstream. **The left plate signal amplitude is about -1.32 V, while the beam current is 2.2 µA. These give a calibration factor of -0.6 V/µA .**

The up plate signal and the down plate signal look quite symmetrical about zero setting of YCB1, but the up plate amplitude appears to be only half of the down plate. These are the raw data without any scaling applied. This discrepancy is likely caused by beam losses that occur on the upstream collimator when the beam is steered upward very hard. This can be seen from Fig. 3, when YCB1 is excited stronger than +12A to steer the beam further upward, the collimator up temperature starts to rise quickly, while the TPM up plate signal starts to turn round and go down. Also, the halo plate signal appears closely the same as the up and down plates. This makes sense.

There is no determinant evidence indicating that the up plate gives a different amplitude of signal response to the beam than the down plate. When a large fraction of 2.2 µA beam falls on the down plate (as there is a kind of flat-top occurring on the down plate), the down plate reads about -1.32 V. **This gives a calibration factor of -0.6 V/µA for the down plate, identical to that of the halo plate and the left plate.**

It's dictated by UCN group that a sufficiently large proton beam spot must be achieved at BL1U end window, target window and target to guarantee safe operation of these elements under full current of 40 µA. Specifically, this requires a beam size of $\sigma_x > 5.5$ mm in the horizontal direction and $\sigma_y > 2.0$ mm in the vertical direction, assuming a Gaussian beam in x and y directions respectively with no correlation. With this beam size, each plate of TPM would detect $> 0.02\%$ of total current. So under full current of 40 µA, this requires $> 40\,\mu A \times 0.02\% = 8\,nA$ for each plate of 5 mm wide. Applying the above calibration factor of 0.6 V/µA, we need to have > 4.8 mV for each plate.

But, the results of BL1U commissioning under full intensity of 40 µA show much higher read-backs from the TPM, which are:

$$\begin{aligned}
\text{TPM Left} &= -1.49\,V,\\
\text{Right} &= -0.00\,V,\\
\text{Up} &= -0.47\,V,\\
\text{Down} &= -0.27\,V,\\
\text{Halo} &= -1.38\,V,
\end{aligned}$$

while the collimator temperature remains at 41°. Vertically, the read-backs are larger than the required values by a factor of 50−100. But, it would not be surprising that the actual beam size gets to 3.3−3.7 mm (1rms) instead of 2.1 mm (1σ under Gaussian assumption). Horizontally, it's even more involved, as the TPM is misaligned. Nevertheless, it's not impossible to get a size as large as 7.0 mm (1rms). Besides, should be pointed out that the beam profile is barely a Gaussian in terms of measurement results. In horizontal direction, there exist asymmetrical distributions in both energy and radial position in the H-minus beam dumped on the stripping foil and therefore extracted down the beamline(s). Vertically, the stripping foil is not necessarily fully dipped into the circulating beam, leading to an asymmetrical profile due to betatron oscillation. These initially asymmetrical distributions are propagated down the beamline and show up at various locations. The asymmetrical tails can be much higher than Gaussian. As an aexample, Fig. 4 shows the profiles measured at monitor B1U:HARP2 under the nominal tune of BL1U.

For interlock purpose, the left plate must detect >1.5% of beam current down 1U, which is >0.6 µA under full intensity of 40 µA. This corresponds to >0.36 V.

For the up and down plates, they must detect >0.02% of beam down 1U, which is >4.8 mV for 40 µA.

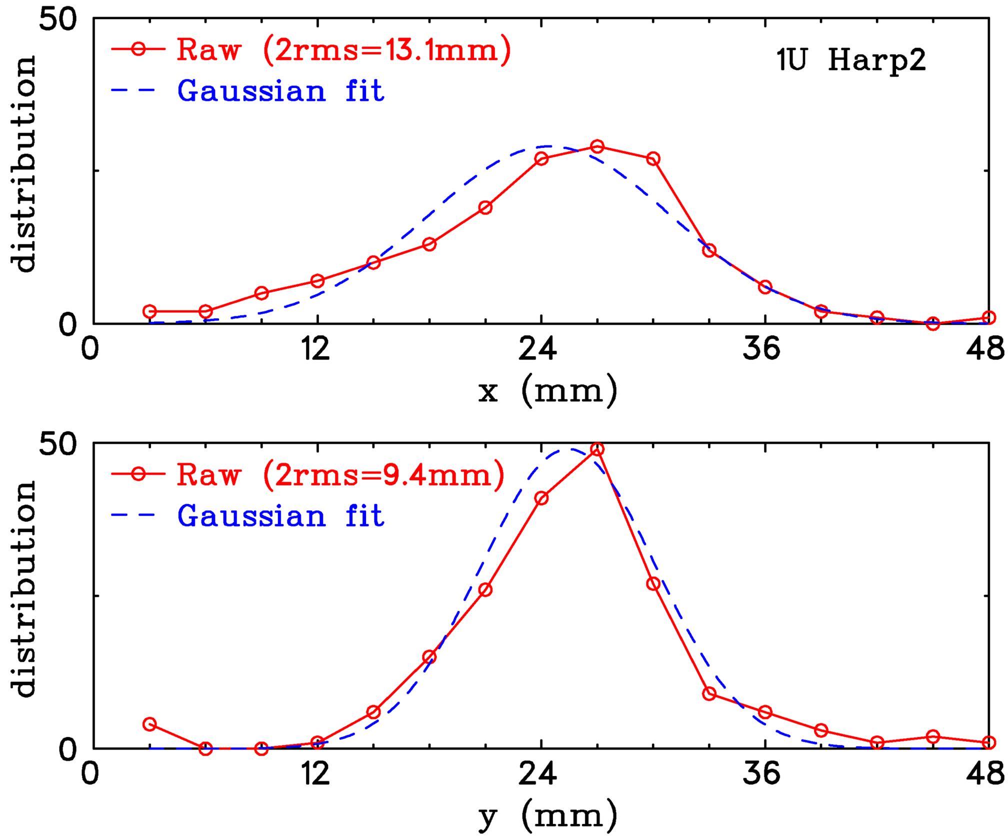

Figure 4: *Beam profiles measured at monitor B1U:HARP2 under nominal tune of BL1U, showing asymmetrical distributions with tails higher than Gaussian.*

3 Estimate of Beam Size from TPM

We estimate the beam size by taking derivative of the TPM signal to reveal the beam profile. Fig. 5 shows the results, where the XCB1 and YCB1 settings in Ampere have been converted to positions by multiplying a kick angle of 0.14 mrad/A of the steerers and kick arms (i.e. transfer matrix elements) of R_{12}=3.1 mm/mrad and R_{34}=5.2 mm/mrad for the horizontal and vertical directions respectively. These values are calculated from the magnet model and beamline optics model. The resulting beam sizes are 1.8±0.2 mm in x and 4.5±0.8 mm in y, which appear larger than the theoretical predictions by about 80% and 40% respectively.

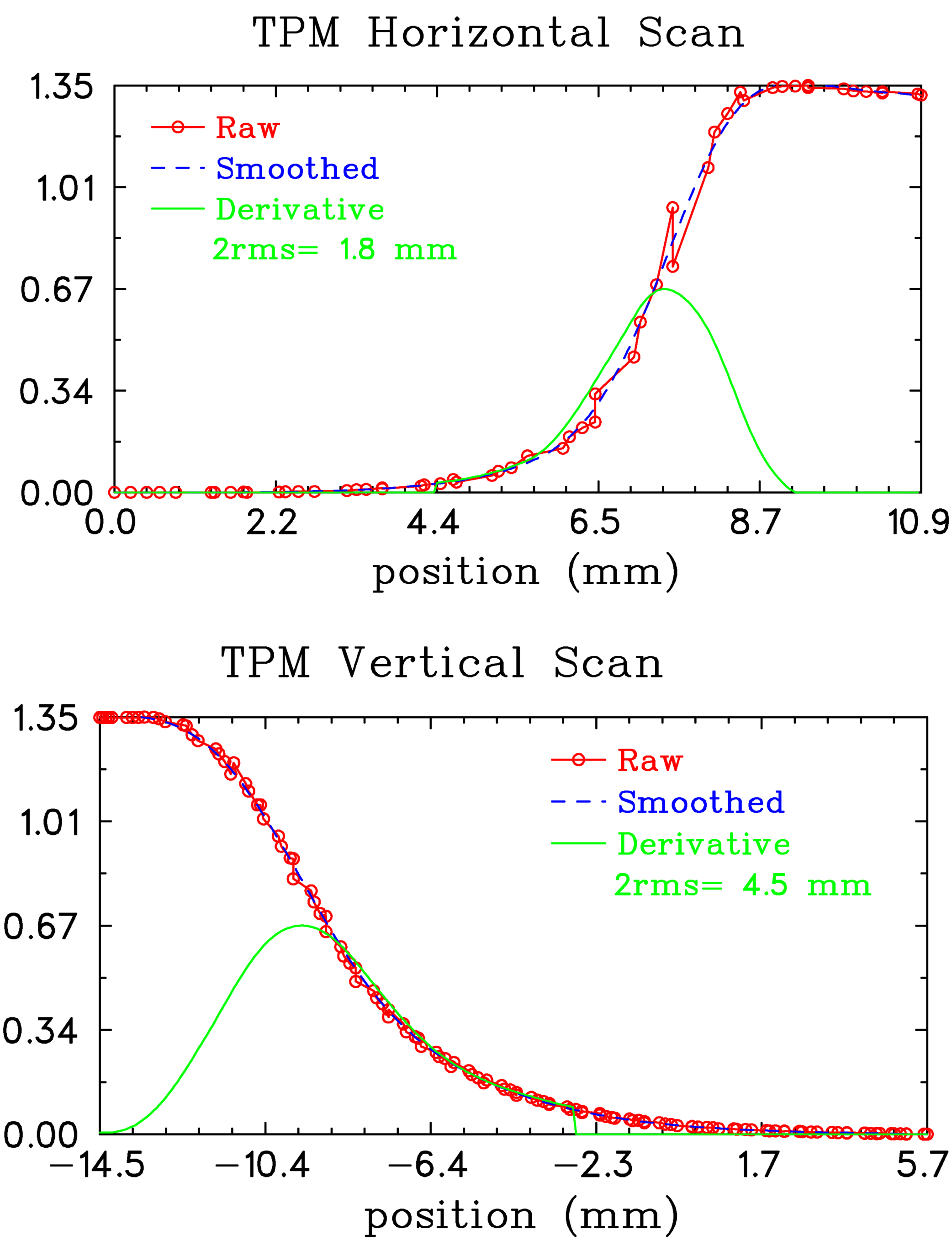

Figure 5: *The TPM scan signals are used to work out the beam profiles and sizes by taking a derivative. The beam distribution is asymmetrical and has a longer tail on the right and top.*

4 BPM Measurements

The BPM's measured beam positions agree quite well with theoretical predictions; the relative deviation is about 30% in terms of magnitudes of elements R_{34} and R_{12}. This is shown in Fig. 6.

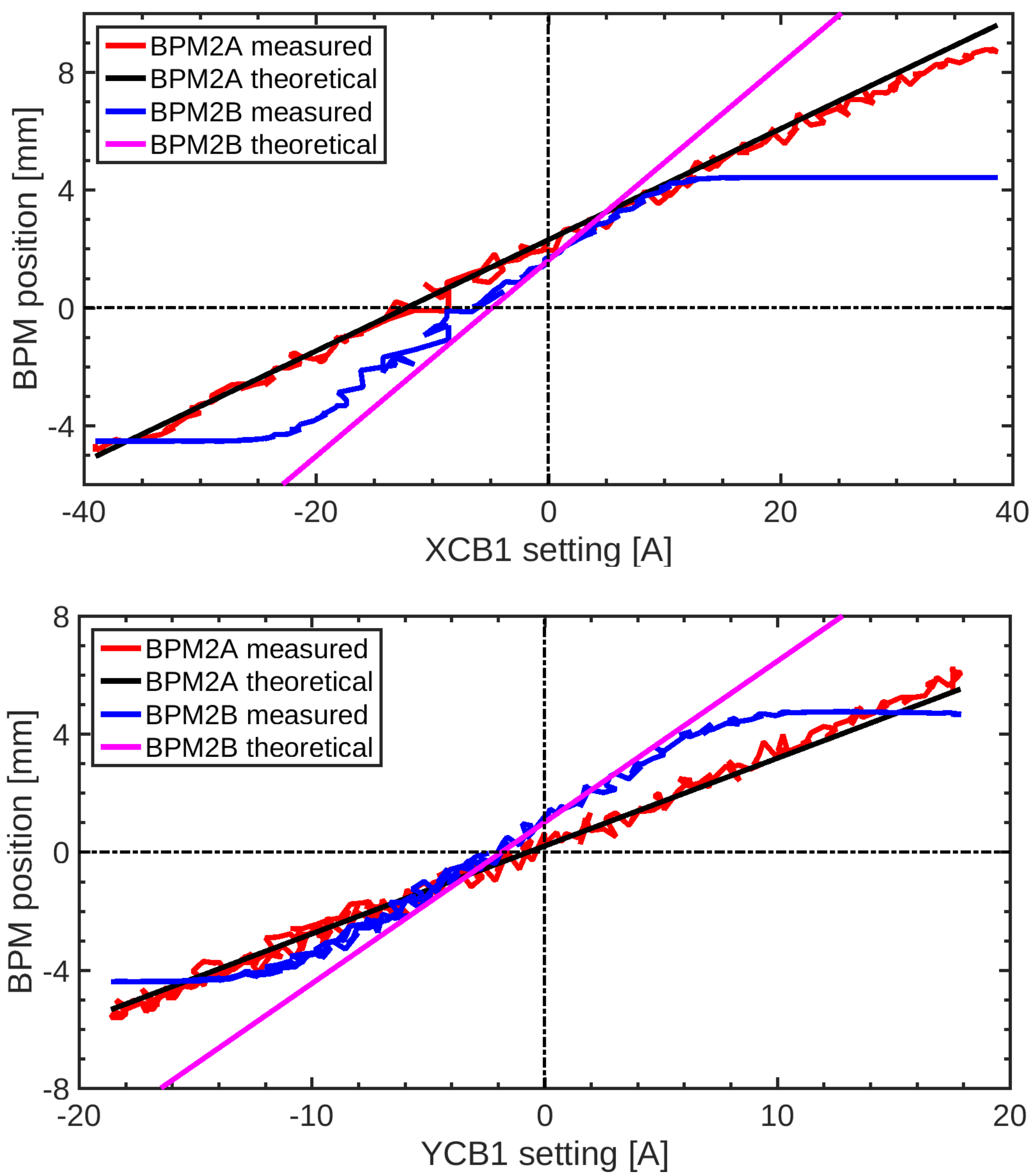

Figure 6: *The BPM's measured horizontal (upper) and vertical (lower) beam positions, in comparison with theoretical predictions. Notice that the BPM2B measured signal gets saturated at* $\sim \pm 4$ *mm. This is arisen from the electronics. Should be mentioned that a positive beam position in the horizontal direction means on the left of pipe axis (looking downstream), while a positive position in the vertical direction means above the axis.*

5 TNIM Calibration

The beam intensity extracted down to BL1V is read from the BL1 adjusted foil current, which has been well-calibrated and reliable. Therefore, the BL1U TNIM reading is calibrated against the adjusted foil current. In DC mode, the calibrated TNIM reading should be equal to the adjusted foil current (as beam losses are minimized to be negligible), while in kicking mode, the calibrated TNIM current should be equal to the foil current multiplying the kicking fraction.

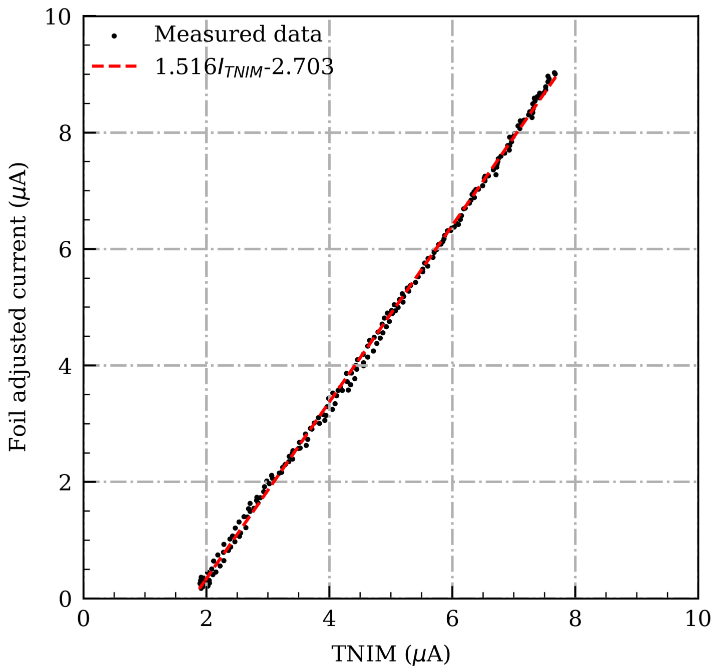

Figure 7: Calibration parameters of TNIM in DC mode. During the measurements, the gain factor and the offset for the TNIM have been set to 1 and 0 respectively in the EPICS page. The TNIM reading still shows an offset of 2 µA. The linearity between TNIM and the adjusted foil current looks good. The calibration parameters are determined through a linear fit.

TNIM calibration factors appear different for different kicking fractions. These are shown in Fig.8 and Table 1.

For kicking fraction(s) not listed in the table, one can use the fitted equations in Fig. 8 to calculate the slope. A constant offset of 1.604 µA can be used.

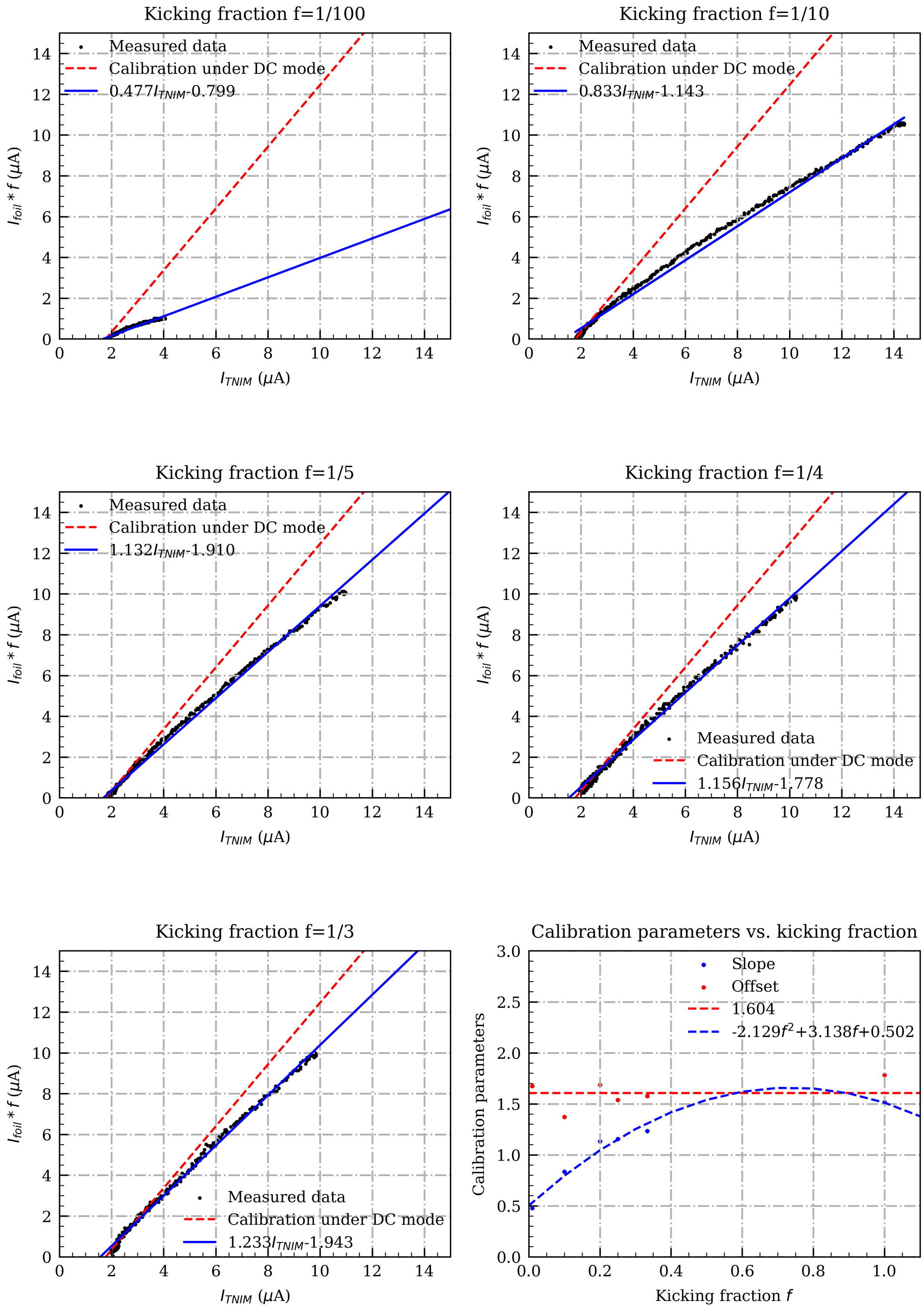

Figure 8: Calibration parameters of TNIM under various kicking fractions. The pulser duty factor is fixed at 92% for all the measurements. The current down to BL1U is adjusted using ISIS slits. The red dashed line represents the calibration curve for DC mode. With the increase of kicking fraction, the calibration curve gets closer to the DC curve. The slope of the calibration curve varies nonlinearly with the kicking fraction.

Table 1: Calibration parameters: $I_{Calibrated}$=Slope*(I_{TNIM} - Offset)

Kicking fraction	Offset (µA)	Slope
1(DC)	1.783	1.516
3	1.576	1.233
4	1.538	1.156
5	1.687	1.132
10	1.371	0.833
100	1.673	0.477

6 BSMs Trip Limits

BSMs 49, 50, 55, 56 and air monitor readings were recorded during the 40 µA commissioning. The raw data is shown in Fig. 9. The maximum readings are listed in Table 2, which can be used to determine the trip limits of these monitors.

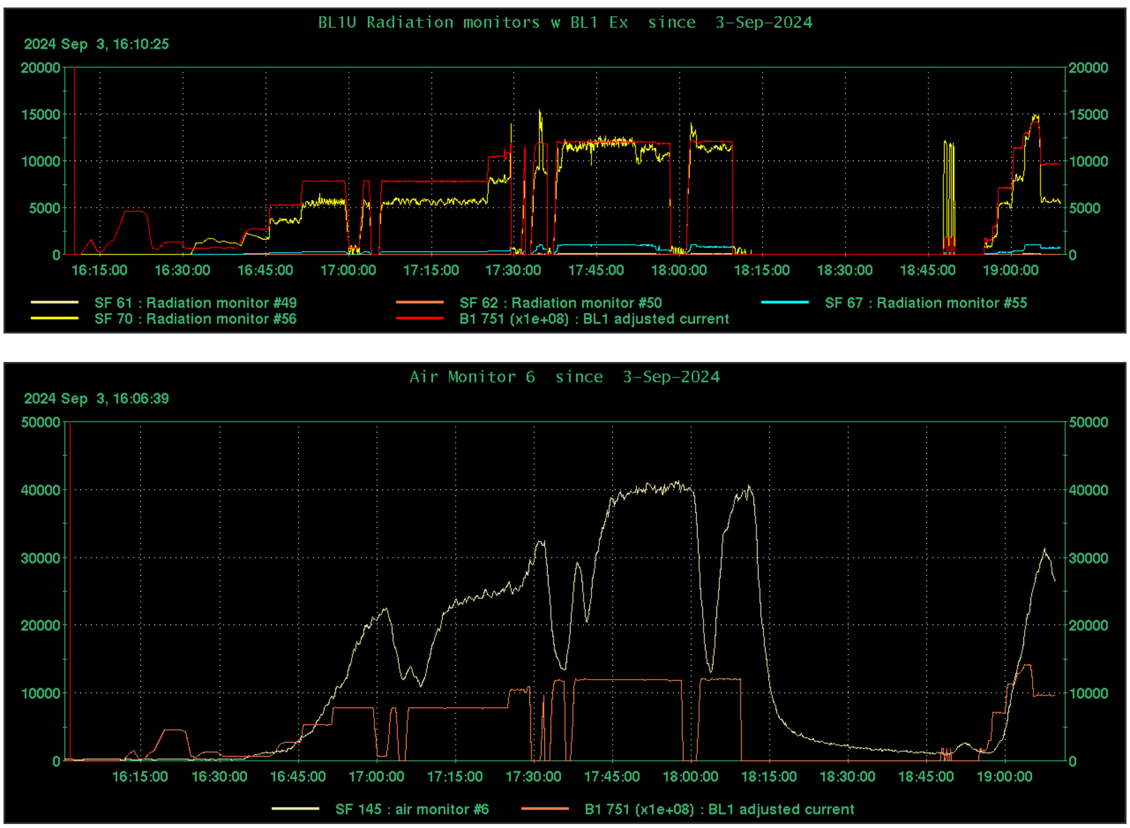

Figure 9: BSMs (upper) and air monitor (lower) readings during the BL1U 40 µA commissioning.

Table 2: Maximum readings of BSMs and air monitor. The BSMs maximum readings occur at 140 µA down to 1V and 35 µA (1/4) kicked to 1U. The air monitor maximum reading occur at 120 µA down to 1V and 40 µA (1/3) kicked to 1U. The BSM55 reading was capped at 1000 mSv/hr by the control system but the actual reading is expected to be higher.

Monitors	Max. reading (mSv/hr)	Current warning level (mSv/hr)	Current trip level (mSv/hr)	Suggested warning level (mSv/hr)	Suggested trip level (mSv/hr)
BSM49	70	100	200	150	300
BSM50	47	125	250	125	250
BSM55	1000	125	250	1500	3000
BSM56	14368	5000	10000	20000	40000
Air monitor	40241 cpm				