LOW-ENERGY INJECTION STUDY FOR TPS BOOSTER RING DURING LINAC MODULATOR DEGRADATION

W. Y. Lin*, H. J. Tsai, T. W. Hsu, T. Y. Lee, C. Y. Hung, B. Y. Huang,
National Synchrotron Radiation Research Center (NSRRC), Hsinchu, Taiwan

Abstract

In early 2025, Linac modulator 3 at the Taiwan Photon Source (TPS) exhibited signs of performance degradation. To reduce electrical stress and prevent an unplanned failure during user operations, BR injection feasibility was evaluated at 130 MeV, 140 MeV, and the nominal 150 MeV. Two compounding mechanisms limit low-energy injection efficiency: increased geometric emittance from the Linac, and degraded BR power supply waveform reproducibility at the earlier injection point on the ramp, which reduces the dynamic aperture. At 130 MeV, the mean BR current of 0.168 mA cannot satisfy the 5-second top-up window. At 140 MeV, a mean of 0.342 mA meets the >0.3 mA operational criterion, and this 140 MeV rescue mode maintained uninterrupted user service throughout the modulator degradation period.

INTRODUCTION

The Taiwan Photon Source (TPS) is a 3 GeV third-generation synchrotron light source. Its injector chain consists of a 150 MeV Linac followed by a booster ring (BR) that ramps beam from the injection energy to 3 GeV at 3 Hz, injecting into the storage ring (SR) in top-up mode to maintain 505 mA [1].

Each top-up cycle must complete within 5 seconds to minimise disruption to user experiments, requiring each BR pulse to deliver >0.3 mA to the SR. In early 2025, modulator 3 showed signs of imminent failure. To mitigate the risk of a catastrophic fault during user time, the modulator voltage was reduced, lowering the Linac output energy below 150 MeV. This paper analyses the two dominant physical mechanisms responsible for the observed performance degradation and reports the operational results of the 140 MeV rescue mode.

EFFECT OF LINAC ENERGY ON BEAM EMITTANCE

The TPS Linac is specified with a normalised emittance of $\varepsilon_n = 50\,\pi$ mm·mrad. The geometric emittance at the BR injection point scales inversely with Linac energy:

$$\varepsilon(E) = \frac{\varepsilon_n \times 0.511\,\mathrm{MeV}}{E}, \tag{1}$$

so reducing the energy from 150 MeV to 140 MeV (−9.3%) and 130 MeV (−13.3%) increases the geometric emittance by approximately 10.2% and 15.4%, respectively. The resulting enlargement of the transverse beam size raises particle losses at the injection septum and during the early ramp phase. The theoretical emittance curve is shown in Fig. 1, and the measured beam profiles during the BR energy ramp (Fig. 2) and the corresponding beam sizes as a function of ramp energy (Fig. 3) are both consistent with this scaling behaviour.

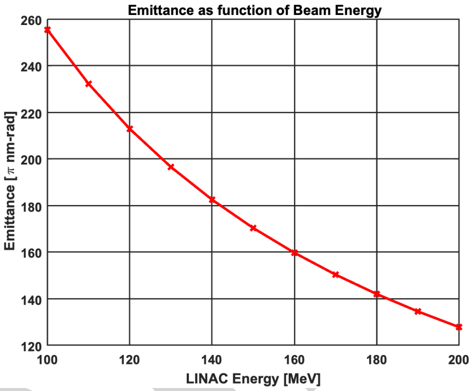

Figure 1: Theoretical geometric emittance vs. Linac energy from Eq. (1) with $\varepsilon_n = 50\,\pi$ mm·mrad.

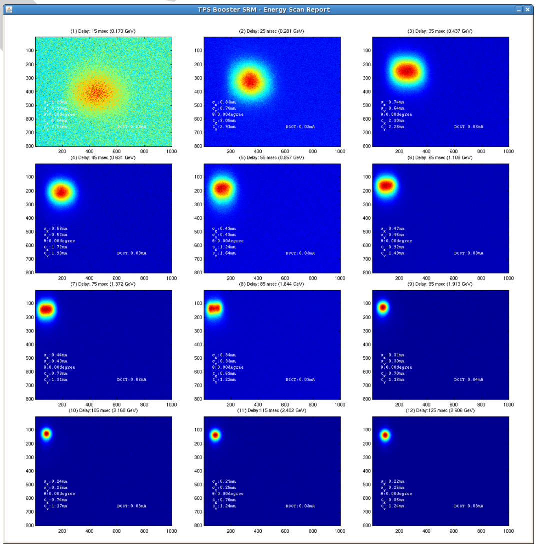

Figure 2: Measured transverse beam profiles at the BR during the energy ramp, recorded at selected delay times from 75 ms to 125 ms (corresponding to beam energies of approximately 1.37–2.60 GeV). The beam size decreases as the beam is accelerated, consistent with the $\varepsilon \propto 1/E$ scaling of Eq. (1).

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[*] lin.lucien@nsrrc.org.tw

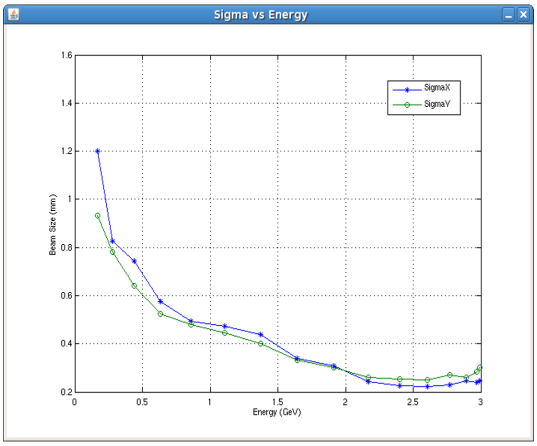

Figure 3: Measured horizontal and vertical beam sizes as a function of beam energy during the BR ramp.

BR POWER SUPPLY STABILITY AT REDUCED INJECTION ENERGY

Previous work [2] established that BR injection efficiency is critically sensitive to the shot-to-shot reproducibility of the booster power supply (PS) waveforms at the injection point. Among all power supplies, the dipole PS (BEND) is the most sensitive: when its normalised tracking error exceeds ±0.2% at the injection point, the captured BR current drops below 50% of its maximum value.

Under nominal 150 MeV operation, injection occurs during a stable, reproducible segment of the ramp and all PS tracking errors remain within their alert boundaries. When the Linac energy is reduced, the injection point shifts to an *earlier, lower-current phase* of the ramp. As shown in the 100-shot PS waveform overlay (Fig. 4), the normalised tracking errors of all power supplies far exceed their alert boundaries at this earlier phase, because the PS waveform is optimised for the 150 MeV timing and has not yet entered its stable regime. The resulting degradation in waveform reproducibility directly reduces the dynamic aperture at the injection point, causing significant particle loss even after successful septum traversal.

The two mechanisms act in the same direction and compound each other: increased emittance enlarges the injected beam and raises septum losses; simultaneously, degraded PS reproducibility reduces the dynamic aperture and amplifies losses during the ramp. The combined effect causes the BR captured current to decrease sharply — and non-linearly — with reducing Linac energy.

EXPERIMENTAL RESULTS

Before interpreting the results, it is important to note that the BR currents reported in this study reflect a filling-pattern-optimised operating point, not the hardware ceiling of the injection system. During user operations, the Linac pulse width is intentionally limited to 256 ns (128 bunches) to ensure a uniform filling pattern in the SR. Under this condition, the normalised bunch current remains consistently near 4 µA/bunch across all three injection energies, confirming that the per-bunch beam quality is well preserved. When the Linac pulse width is extended to accommodate 332 bunches, the BR total current readily exceeds 1.25 mA at 140 MeV (Fig. 5), approximately three times the value reported under standard user conditions. The comparisons in this study are therefore made on a consistent, operationally representative basis across all three energies.

The injection septum voltage and timing were adjusted for each energy point to match the corresponding injection phase on the BR ramp (98.6 V / 12500 µs at 140 MeV; 104.95 V / 13730 µs at 150 MeV).

At 130 MeV, $I_{\mathrm{BR}}(\mathrm{mean}) = 0.168$ mA, well below the 0.3 mA threshold. The histogram exhibits a strongly left-skewed distribution peaked near 0.10–0.15 mA. The high valid pulse count (2919) reflects the large number of pulses required per top-up cycle — not better performance. Top-up injection cannot be completed within 5 seconds. Operation at 130 MeV is unsuitable for user service.

At 140 MeV, $I_{\mathrm{BR}}(\mathrm{mean}) = 0.342$ mA, exceeding the 0.3 mA threshold. The histogram shows a near-Gaussian distribution peaked at 0.35–0.40 mA. The low pulse count (669) confirms that each top-up cycle is completed with only a small number of injections, with stable shot-to-shot performance. The 140 MeV rescue mode satisfies all operational criteria.

At 150 MeV (nominal reference), $I_{\mathrm{BR}}(\mathrm{mean}) = 0.436$ mA with a maximum of 0.566 mA, providing the performance baseline.

The key results are summarised in Table 1 and illustrated in Fig. 6.

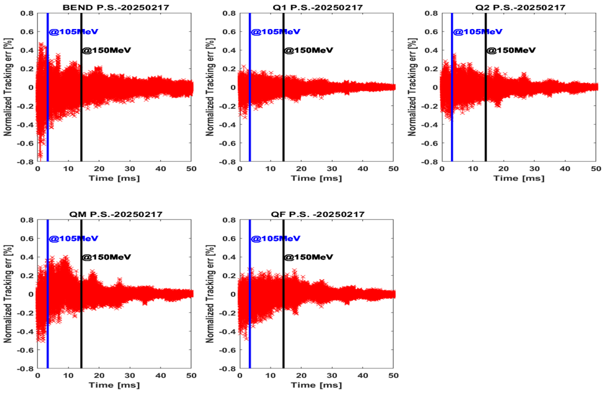

Figure 4: BR PS 100-shot waveform overlay at the 105 MeV and 150 MeV injection points. At the earlier injection phase, all PS tracking errors far exceed the alert boundaries of [2].

IMPLEMENTATION AND SIGNIFICANCE

The 140 MeV rescue mode was deployed with modulator 3 voltage reduced to 31.02 kV, injection septum at 98.6 V, and injection timing at 12500 µs. Top-up injection continued at 3 Hz with the SR current maintained stably at 505 mA, completing each cycle within the 5-second window with zero unplanned beam downtime.

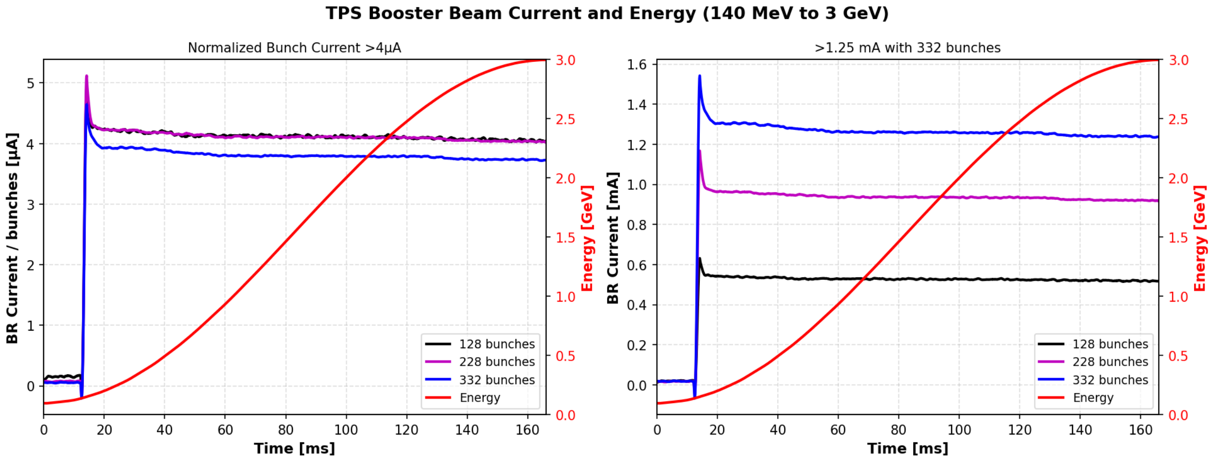

Figure 5: BR beam current at 140 MeV for 128, 228, and 332 bunches. Left: normalised bunch current (~4 μA/bunch for all filling modes), confirming preserved per-bunch quality. Right: total BR current exceeding 1.25 mA with 332 bunches, demonstrating that the reported values reflect an operationally constrained, not hardware-limited, operating point.

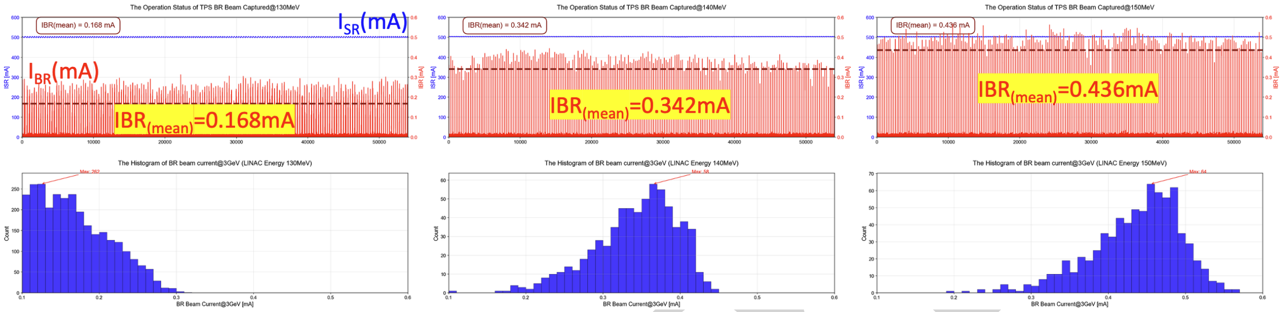

Figure 6: BR beam current time series (upper panels) and histograms at 3 GeV (lower panels) for Linac injection energies of 130 MeV (left), 140 MeV (centre), and 150 MeV (right). Dashed lines indicate I_{BR} (mean) for each case. The strongly left-skewed distribution at 130 MeV contrasts with the near-Gaussian profiles at 140 MeV and 150 MeV.

Table 1: Summary of BR Injection Performance

Metric	**130**	**140**	**150 MeV**
I_{BR} mean (mA)	0.168	0.342	0.436
I_{BR} max (mA)	0.313	0.444	0.566
Valid pulses (>0.1 mA)	2919	669	754
Meets >0.3 mA criterion	No	Yes	Yes
Top-up within 5 s	No	Yes	Yes
User service viable	No	Yes	Yes

At 140 MeV, the BR PS waveform reproducibility remains within acceptable bounds and the 9.3% emittance increase is still within the tolerance of the dynamic aperture — establishing 140 MeV as the lower feasibility limit for TPS injection under reduced modulator voltage conditions. At 130 MeV, the two mechanisms compound beyond this limit, making user operation impossible.

This work demonstrates the extended utility of the BR PS waveform monitoring tool [2] beyond fault diagnosis: its quantitative analysis of injection-point waveform reproducibility enabled rapid assessment of each candidate energy, replacing time-consuming trial-and-error tuning. The combined diagnostic framework of emittance scaling analysis and PS waveform reproducibility evaluation offers a broadly applicable methodology for facilities facing analogous injector hardware constraints.

REFERENCES

[1] *TPS Design Handbook*, version 16, NSRRC, Taiwan, Jun. 2009.

[2] W. Y. Lin *et al.*, “TPS booster power supply performance experiment and monitoring program”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 3261–3263. `doi:10.18429/JACoW-IPAC2024-THPG07`.