CURRENT STATUS OF THE UPGRADE AND OPERATION OF THE NSRRC TPS LINAC PULSE HIGH-POWER RF SYSTEM

W. Y. Chiang, Y. C. Chang, A. P. Lee, K. L. Tsai, C. L. Chen, H. P. Chang, M. C. Chou, H. P. Hsueh, NSRRC, Hsinchu, Taiwan
H. Matsumoto, KEK, Ibaraki, Japan

Abstract

The NSRRC Taiwan Photon Source (TSP) pre-injector system includes a DC thermionic electron gun, a Sub-Harmonic Pre-Buncher, a Primary Buncher, a Final Buncher, three S-band LINAC sections, and three 35-MW S-band-Klystrons. While the original klystrons were Thales TH2100A, recent instability and shorter tube lifetimes led NSRRC to upgrade to the E37310A klystron from CETD. This work analyses the RI-designed pre-injector system, implements modifications to ensure compatibility with the CETD E37310A, and ensures the supply of the required RF power. In August 2023, using the THz FEL pulse RF system, NSRRC upgraded the TLS pre-injector pulse RF system. Following six months of stable operation, upgrades to all three TPS pre-injector pulse RF systems began in 2024. This paper presents installation, modulator modifications, testing, and operational status of the first two TPS systems, completed in September 2025 and February 2026.

INTRODUCTION

The TPS pre-injector system is designed and manufactured by Research Instruments (RI) as a turnkey system, as shown in Figure 1. It consists of five major components:

1. Direct current (DC) thermionic electron gun: supports single-bunch mode (pulse width 1 ns, output charge 2 nC) and multi-bunch mode (pulse width 200 ~1000 ns, output charge 5 nC). The maximum repetition rate for both modes is 5 Hz. After acceleration in the electron gun, the beam energy reaches 90 keV.
2. Sub-harmonic pre-buncher: a single-cavity resonator operating at 499.654 MHz that compresses the electron beam pulse width to below 1 ns.
3. Primary buncher: consists of four resonant cavities operating in the 2π/3 mode at 2997.912 MHz (40 °C). It accelerates the electron beam from 90 keV to 300 keV and requires 2 MW of radio-frequency (RF) input power.
4. Final buncher: consists of 16 resonant cavities operating in the 8π/9 mode at 2997.912 MHz (40 °C). It further accelerates the beam from 300 keV to 3 MeV and requires 3.5 MW of RF input power.
5. S-band linear accelerator: includes 156-cell traveling-wave structure operating in the 2π/3 mode at 2997.912 ± 0.03 MHz and maintained at 38 ~ 42 ± 0.1 °C. This final stage consists of three S-band accelerator sections, which raise the beam energy to 150 MeV. Each section requires roughly 16 MW of RF power.

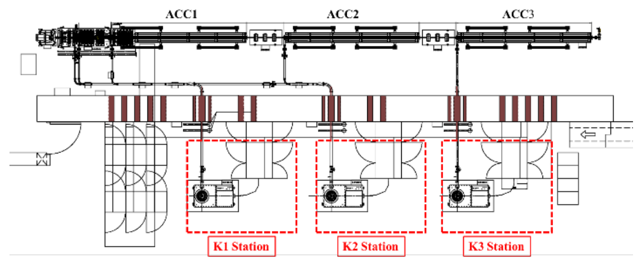

Figure 1: TPS pre-injector system [1].

KLYSTRON UPGRADE

The TPS pre-injector system uses three high-power RF stations in pulsed mode: K1 supplies RF power to the Primary Buncher, Final Buncher, and LINAC-ACC1, while K2 and K3 supply RF power to LINAC-ACC-2 and ACC-3. All stations use the Thales TH2100A Klystron (Fig. 2(a)), whose electron gun has a high arcing rate, leading to failures. Additionally, manufacturing quality has declined in recent years, shortening operational lifetimes and reducing TPS reliability. To address these issues and improve reliability, a Klystron Upgrade Program was launched in 2024 to replace the TH2100A with the E37310A Klystron (Fig. 2(b)) from Canon Electron Tubes & Devices (CETD). Table 1 shows that the E37310A's performance and operating parameters are similar to those of the TH2100A, fully meeting TPS LINAC requirements. Experience from the Taiwan Light Source (TLS) LINAC upgrade demonstrates that the E37310A enhances operational stability and light-source performance. The upgrade also requires modifications to the high-voltage insulating oil tank and the pulsed modulator system to ensure long-term reliability.

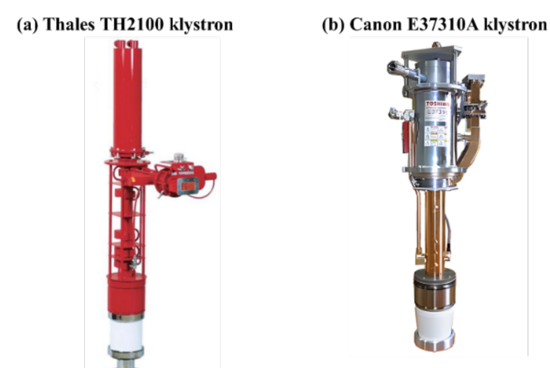

Figure 2: (a) Thales TH2100 Klystron [2] and (b) CETD E37310A Klystron [3].

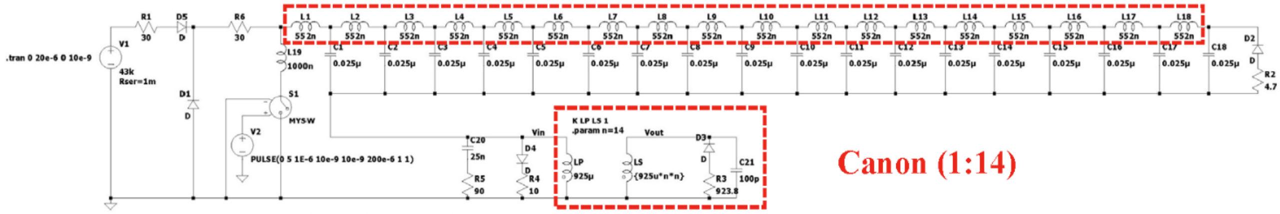

Figure 3: Circuit model of the newly designed PFN in the pulsed modulator (1:14 turns ratio).

Table 1: Comparison of the Specifications of the Thales TH2100 and CETD E37310A Klystrons

Measurement	Thales TH2100	CETD E37310A
Frequency	2998.5 ± 1 MHz	2998.5 ± 1 MHz
Peak Cathode Voltage	272 kV	295 kV
Peak Cathode Current	286.2 A	310 A
Drive Power	126.7 W	291 W
Peak RF Output Power	35.1 MW	35.6 MW
Pulse Width (duration, 75%)	6.5 µs	7.5 µs
Pulse Width (duration, RF)	4.5 µs	4.5 µs
Pulse Transformer Turn Ratio	13	14
Klystron Impedance	5.62 Ω	4.7 Ω

KLYSTRON MODULATOR UPGRADE

The RI-designed pulsed modulator incorporates a charging power supply with a maximum output voltage of 45 kV, chosen to ensure stable long-term operation and maintain an appropriate voltage breakdown margin. Under matched conditions, the maximum deliverable primary-side voltage is 22.5 kV. Understanding the klystron operating conditions to determine the pulse transformer turns ratio is an important step, and it also affects the design of the Klystron oil tank. Next, theoretical estimates and numerical simulations will be performed to determine the most suitable turn ratio for the pulse transformer. PFN simulations and design optimization are performed using LT-Spice, as shown in Figure 3.

The original PFN had 18 sections, each with 800 nH inductance and 25 nF capacitance. The PFN impedance was 5.66 Ω, matching RI's 5 ~ 6 Ω range. The new PFN design keeps 18 sections due to space limits. TH2100A runs at 272 kV and 286.2 A with a secondary impedance of 950 Ω. A 1:13 transformer gives a primary impedance of 5.62 Ω. E37310A runs at 291 kV and 315 A with a secondary impedance of 923.8 Ω; with a 1:13 turns ratio, the primary impedance is 5.47 Ω. Achieving −300 kV requires a 47 kV charging voltage, which is over the limit. With a 1:14 turns ratio, the primary impedance is 4.7 Ω. It needs 43.5 kV to reach −300 kV, within specs. At 1:15, the primary impedance drops to 4.1 Ω, and 40 kV is required. With fixed PFN sections, adjusting the turns ratio changes the output waveform and pulse width. At the same charging voltage, the pulse energy is 397 J for a 1:14 ratio and 403 J for a 1:13 ratio, showing close agreement, but 1:13 gives lower peak power and a wider pulse width. The TPS pre-injector requires a flat-top duration of over 2 µs. With a 1:15 ratio, FWHM is 3.73 µs. Considering limits, a 1:14 ratio is optimal.

A new inductor string is installed in parallel with the original inductors to achieve the required 552 nH. The final PFN configuration and installation are shown in Fig. 6.

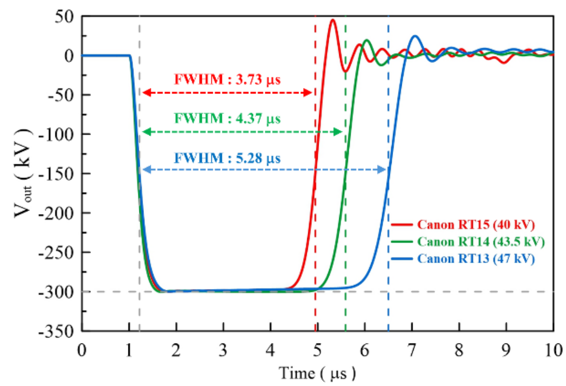

Figure 4: Output voltage waveform analysis of an 18-section PFN design: pulse transformer turns ratio 1:13 (FWHM: 5.28 µs, blue), 1:14 (WHM: 4.37 µs, green), 1:15 (WHM: 3.73 µs, red).

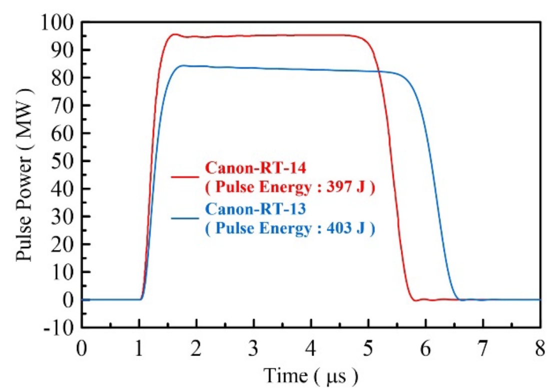

Figure 5: Pulse power versus pulse duration for different pulse transformer turns ratios: 1:13 (blue) and 1:14 (red).

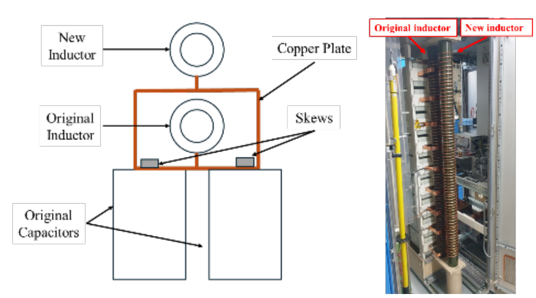

Figure 6: PFN pulsed modulator: revised configuration diagram and photograph of the completed installation.

OPERATING STATUS OF THE NEW KLYSTRON AND MODULATOR

Phase I of the TPS pre-injector upgrade concluded in February 2026, following the technical modifications described earlier. K1 and K2 Stations received the E37310A Klystron replacements and pulsed modulator upgrades. Figure 7 outlines the new K1 station setup, and Figure 8 shows installation photos. The upgraded PFN inductor stack allows fine-tuning by inserting metal tubes, illustrated in Figure 9. By placing two aluminum tubes and adjusting their spacing, the flat-top duration of the voltage waveform can be extended to 2 µs. Under operational conditions—a 3 Hz pulse rate, 4.5 µs RF pulse width, 281 kV cathode voltage, and 305 A cathode current—the E37310A produced 36 MW of RF output power (Figure 10), confirming correct impedance matching and stable modulator operation, as designed.

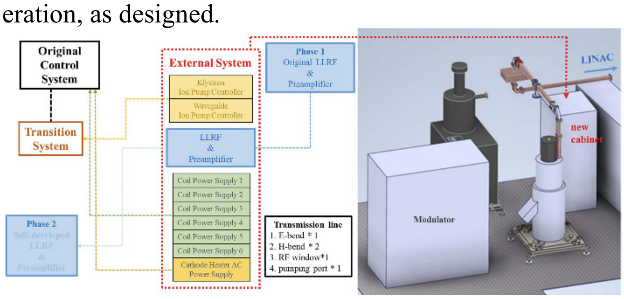

Figure 7: Revised K1 Station configuration.

Figure 8: Revised K1 Station.

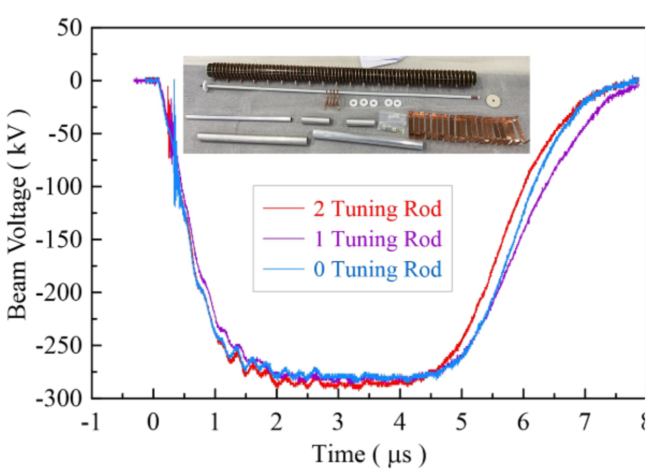

Figure 9: Comparison of voltage waveforms with PFN inductance tuning: no aluminium tube (blue); one aluminium tube (purple); two aluminium tubes (red).

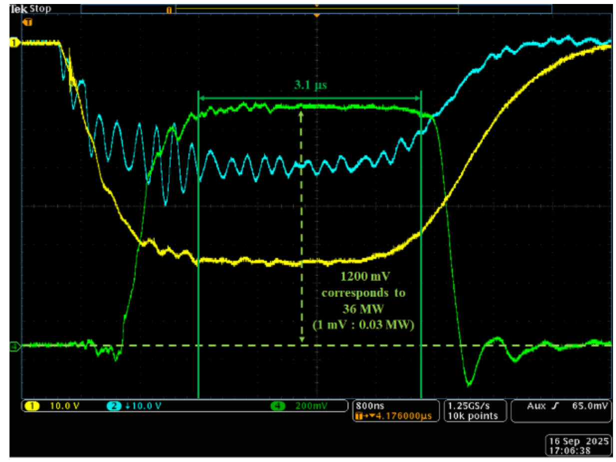

Figure 10: E37310A Klystron cathode voltage (yellow), cathode current (blue), and RF output power (green).

CONCLUSIONS

The redesigned pulsed modulator system achieves a 3.1 µs voltage flat-top, closely matching simulation results and meeting TPS operational requirements, as established throughout the upgrade process. The improvements also reinforce NSRRC's in-house development capability and enable plans for future system enhancements. Rigorous testing of TH2100A and E37310A established standardized operating and maintenance procedures, raising safety, efficiency, and reliability. Building on these upgrades, a Phase II plan will be developed to assess enhancements to the LLRF and control systems. A robust, pulsed, high-power RF system will support studies of higher-energy electron injection, allowing staged increases in pre-injector electron energy toward the 200 MeV target.

REFERENCES

[1] TPS 150 MeV Linac Documentation (2008).

[2] A. Beunas, "THALES RF Sources for Accelerator Recent Developments", the CompactLight 2nd Midterm Meeting, Helsinki, Finland, July 2019.

[3] Microwave Tubes Product Catalog, April (2025). https://etd.canon/en/download/files/microwave_tube_catalog_EN.pdf