ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPM003

RETURN OF EXPERIENCE IN THE COMMISSIONING OF THE NEW CLS LINAC INJECTOR

F. Le Pimpec*, X. Stragier, X. Shen, J. Stampe, C-L. Randall, W. A. Wurtz,
D. Beauregard, G. Bilbrough, T. Batten, M. Bree, M. A. Ratzlaff, J.M. Vogt,
C. Baribeau, E. Heredia, E. Nebot del Busto, S. Saadat,
T. Sove, J. Doucette-Garr, T. McKeith, A. Rosset, D. Schneberger,
B. Dube, A. McCormick, R. Shree Kotha, S. Smith, B. Smith,
K. McKeith, D. Bergstrom, S. Kolmakov, A. Nikolaichuk,
J. Erikson, S. Carriere, L. Lin, B. Schneider, B. Schreiner,
J. Campbell,
Canadian Light Source, Saskatoon, Canada
J. Hottenbacher, K. Dunkel, M. Grewe, A. Vanselow, B. Keune,
P. Biegun, A. Kraemer, W. Korte, C. Piel
RI Research Instruments GmbH, Bergisch Gladbach, Germany

Abstract

After about 60 years of service the 2856 MHz LINAC injector of the Canadian Light Source (CLS) has been retired to make space for a new 3000.24 MHz LINAC injector, the frequency of which is a multiple of the 500.04 MHz CESR-B type superconductive radio frequency cavity used in the CLS storage ring. The new CLS LINAC injector has been designed and built by RI Research Instruments GmbH. The design is based on their robust S-band RF traveling wave accelerating structures technology, already serving other laboratories in the USA, Australia, Taiwan, Switzerland and Sweden. In order to save money and space the CLS has replaced its six Accelerating RF structures, each 3.05 meters long, delivering 250 MeV electron beam by three 5.26 m long accelerating structures that will deliver the same beam energy by use of a SLED system. We are reporting on the progress of the commissioning of this new injector.

BACKGROUND

The new CLS turn-key LINAC as a new injector for the CLS storage ring, operates at 1 Hz for beam operation and is capable of 10 Hz for RF conditioning. It comprises a 90 keV DC thermionic gun, pulsed with a 500.04 MHz modulated grid, a 500.04 MHz Subharmonic Pre-Buncher (SPB), a Pre-Bunching Unit (PBU) and a traveling wave Final Bunching Unit (FBU) both operating at a frequency of 3000.24 MHz to match the 6th harmonic of the CLS storage ring frequency [1]. The core acceleration is provided by three 5.26 m long S-band traveling wave accelerating structures (ACC1,2 & 3), with two of them being powered through one SLED [2]. The layout of the machine is shown in Fig.1 with the overall results achieved until December 2024. The design of the LINAC is very similar to the one initially delivered by Accel Instruments GmbH to Paul Scherrer Institute for the Swiss Light Source [3]. The installation of the injector was completed in early August 2024 followed by its commissioning.

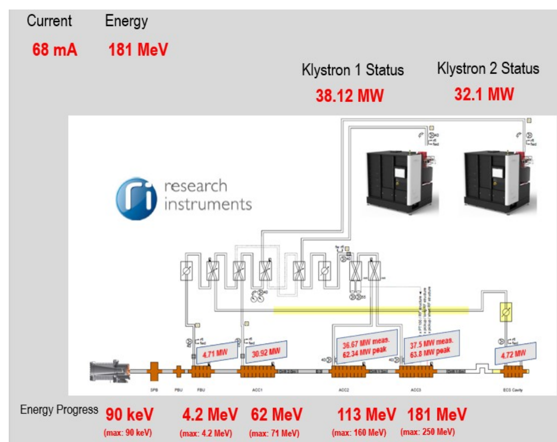

Figure 1: Maximum values achieved by the LINAC in terms of RF power in the RF structures and the energy measured past the Energy Compression System (ECS) used as spectrometer

PRECOMMISSIONING CHECKS

After their installation in the LINAC tunnel, all magnets: steerers, solenoids, and quadrupoles, were tested for basic polarity and performance. The magnets were energized at a low test current and checked with a handheld magnetic field shape indicator (Magnaprobe^{TM} Mark II). Instances of incorrect connections (open circuits, inconsistent polarity, etc.) were identified easily and resolved. The quadrupoles from the The Medium Energy Beam Transport (METB) located between ACC1 and 2 were characterized magnetically in the CLS magnet laboratory and surveyed for mechanical and magnetic alignment.

5 YAG:Ce screens in the LINAC were retrofitted with black backing plates with engraved cross hairs mounted

* frederic.le.pimpec@lightsource.ca

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPM003

directly behind them as to ease the camera focusing. A Faraday Cup (FC) located near the gun exit and connected to an oscilloscope is used to monitor the pulse shape and charge of the electron beam coming from the gun

Non-destructive diagnostics were also installed to measure the beam charge at various location along the LINAC, wall current monitor (WCM), fast current transformers (FCT) and a calibrated Integrating Current Transformer (ICT). Button beam position monitor (BPM) upstream of ACC1, and cavity BPMs, coming from our defunct LINAC, were installed by CLS downstream of each ACC. All are read by Instrumentation Technology Libera Spark EL units, which are sensitive to the 500 MHz component of the BPM signals. The BPMs were commissioned by steering the beam in X and Y, and comparing the position readings with the beam displacements observed on the nearby YAG screens.

RF CONDITIONING

LLRF waveforms that are sent to the klystron are generated by a table of integer values defining in sequence each transition of each waveform. High frequency structure in the waveform can be numerically smoothen prior to sending them to the LLRF. The LLRF interface allows for setting the amplitude and width of the klystron pulse, along with timing features necessary to define the pulse produced by the SLED cavity. To assist with RF conditioning, we also implemented two forms of basic scripting: One for the LLRF and one for a charging capacitor power supply (CCPS) voltage, which controlled how the modulator amplified the signal from the LLRF (thereby the output RF power). The LLRF script allows users to steadily increase the LLRF amplitude or pulse width. The LLRF script included checks (vacuum quality) and fail-safes, verification on safe operating points with regards to the klystron saturation point. The SLED systems suffered from a temperature stability issue, corrected initially with thermal insulation and a tuning issue that resulted in a high reflected RF power. Before retuning mechanically the SLED cavities, the tuning of each cavities was achieved by raising the temperature of each cavities using bakeout heat tapes. The overall SLED frequency to follow the storage ring change of frequency is adjusted by changing the temperature using the cooling water from the chiller.

From September to December 2024 the 3 accelerating structures (ACC1,2 and 3), the SPB and the PBU exhibited issues. The accelerating structures were conditioned with short pulses while increasing the klystron power output of 38 MW. When reached the power would go down to zero and the pulse length increased. As the processing was ongoing the structures were conditioned in a more aggressive manner by not reducing the power significantly after each breakdown. The pulse length was also increased too quickly. As a result, the structure faced a more explosive emission RF conditioning than an evaporation RF emission which helps smoothing the surface or smoothing out sharp edges that is the remnant of an explosive emission of a field emitter. Additional to that, the modulators did not behave as expected and immediate support by the vendor was provided. The summary of the first months of operation and issues encountered by the modulator are shown in Fig.1.

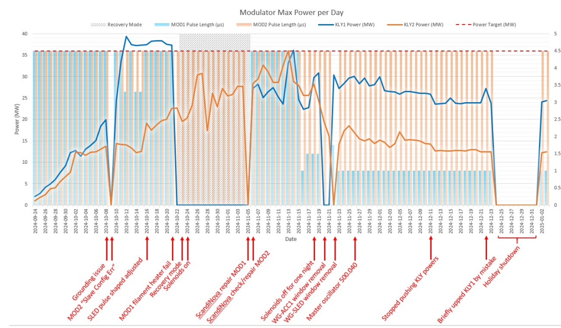

Figure 2: Klystron power output into the RF structures (FBU, ACC1, ACC2 and ACC3, with or without SLED until December 2024

By end of December 2024, the RF structures were not conditioned to their expected performance that would allow a delivery of an electron beam of 250 MeV as defined in the technical specifications. However, a stable point of operation was used to try to provide a beam that could be injected in the CLS storage ring. Unfortunately in January 2025, the values obtained on the accelerating structures could not be achieved anymore. Decision was taken to stop operation and inspect visually all RF components including the SPB and PBU cavities who did not perform. As expected, pitting and some discoloration were found on the Input Couplers (IC) of the ACC structures; pitting diminishing as we move downstream of the IC towards the output couplers (OC). The RF pick up installed at the beginning and end of the structures were inspected and due to heavy pitting, were removed and replaced by RF plugs. Every components that could be RF tested was RF tested (38 MW and 4.5 μs): RF loads, RF windows and RF directional couplers. The RF windows were removed given their conditions although they passed RF testing. Two RF loads were sent to the vendor after they failed RF testing. All other components were reassembled and the full waveguides tested to our satisfaction.

Past discussion with international colleagues it was decided to RF test slowly ACC3 after a bakeout to 150°C. Fig.3 summarizes the conditioning operation and issues encountered by ACC3 (from end of March 2025) until the overall bakeout of the LINAC, end of April 2025. The ACC3 RF conditioning result tends to support the conclusion of an adequate RF design. SPB cavity was RF conditioned succesfully at 450 Hz after replacement of its RF coupler and with different solenoid field strength.

LOCALIZING THE BREAKDOWNS

As the RF conditioning did not go as planned, it was necessary to understand the location of the breakdowns. Traditionally one can use with the help of 2 directional couplers the location of the breakdown through the RF forward and

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPM003

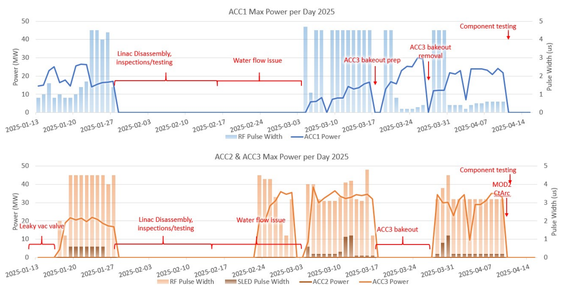

Figure 3: RF power sustained by ACC1, ACC2 and ACC3, with or without SLED until April 2025

reflected power [4, 5]. The other method that was used successfully at SLAC in the early 2000, and then used at other labs: KEK, DESY etc. is to use microphones [6–8]. CLS implemented the two techniques and the results displayed in Fig.4 show the very good correlation of the two techniques.

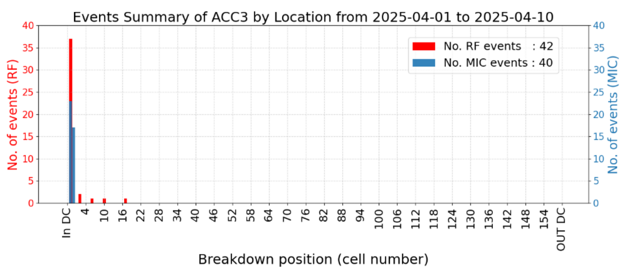

Figure 4: Breakdown localization distribution in ACC3. Red and blue bars represent events reconstructed with directional coupler and microphone data respectively.

BEAM COMMISSIONING

Beam commissioning occurred interleaved with RF conditioning during the original attempt to provide beam for the booster. As with any such activity, there is danger of equipment damage, even when being careful. The beam commissioning effort resulted in a 173 MeV electron beam that we were able to capture and accelerate in the booster to the extraction energy just before the holiday shutdown at the end of 2024. The capture efficiency was poor, but this is believed to be due to the needed booster ring magnet injection energy scaling not being entirely linear. When we resume beam commissioning, we will adjust the transverse tunes over the booster ramp to avoid resonances and improve capture efficiency. The energy spread and beam centroid stability are essential parameters for ensuring reliable booster capture. The beam centroid was improved by placing thermal insulation on the SLED cavity. Unfortunately, we were unable to reproduce these results in January of 2025 after the holiday break as the accelerating structures showed increased arcing. Beam commissioning activities were paused in order to investigate the breakdown issues in the accelerator sections.

SUMMARY

The overall timeline summary of the operation since September 2024 to April 2025 are provided in Figs 2, and 3 for the RF power seen by the RF structures.

The use of the RF and acoustic localization of the breakdowns were in agreement and pointed to the entrance of the structures. The visual inspection carried out in February 2025 had shown heavy pitting on the iris of the input coupler, while disappearing when driving, very carefully, a boroscope through the first cells of the RF structures. The visual inspection extended to RF pick ups on all ACCs, the SPB, PBU and FBU, as well as the RF input couplers on SPB and PBU, see Fig.1.

Out of the results obtained until December 2024, a few key decisions were taken by the commissioning team until April 2025. RF pickups were removed from all the RF ACC structures and the holes were plugged with specially made blanks. Directional couplers were installed at the end of each ACC structure. The input couplers on SPB and FBU were removed and sent to RI for sand blasting, as copper color was observed instead of the color of the expected ceramic, and reinstalled. The SPB structure was then successfully reconditioned with its own power supply at 450 Hz. A combination of temperature stabilization at the SLED, SLED chiller, and modulator room, as well as, the saturation adjustments on the modulators, resulted in a large improvement in energy stability.

A quick program to install microphones and a software to read their output through repurposed ADCs was launched. In less than 3 weeks microphones could be read by a CLS made advanced software. A change of strategy in our RF conditioning was operated such that a less aggressive conditioning method was used. A bakeout was performed on one structure and with a less aggressive RF conditioning, results obtained showed good improvement in term of field achieved and stability for a given power and pulse length, prompting the combined (RI and CLS) team to agree to bake as much of the LINAC as possible. The commissioning has resumed by slowly reconditioning the RF structures. We target an equivalent output energy of 180 MeV from the LINAC with a breakdown rate of less that 1 breakdown per 0.1 million pulses before injecting an electron beam into the booster ring. Shall the RF conditioning go well, the team expects a possible beam commissioning by mid of July 2025 for an injection in the booster by end of July 2025 at the earliest.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the work by the staff of the technical service department for having dismantled and installed the new LINAC from RI Research Instruments GmbH in record time. The authors also would like to acknowledge all the volunteers from the Science, IT division who helped staffing the shifts, including nights and weekend. The authors are also recognizing all the efforts by the Control, technical and engineering departments for their prompt assistance in all the issues encountered. The CLS

ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPM003

and RI team acknowledge the input from colleagues from CERN (W. Wuensch), SLAC (V. Dolgashev), MAXIV (D. Kumbaro) and Elettra (N. Shafqat) for their time in sharing their experience on conditioning their RF structures. The CLS receives funding from the Canadian Foundation for Innovation, the Natural Science and Engineering Research Council of Canada, the University of Saskatchewan, the Canadian Institute for Health Research and the Government of Saskatchewan.

REFERENCES

[1] CLS machine description is found under Facilities and Machine, https://www.lightsource.ca/facilities/machine.php.

[2] SLED: A METHOD OF DOUBLING SLAC's ENERGY, https://s3.cern.ch/inspire-prod-files-0/068ed22dae5ba0bab8bcf19f9dcac092.

[3] M. Peiniger, C. Piel, H. Vogel, and P. vom Stein, "A 100 MeV Injector Linac for the Swiss Light Source Supplied by Industry", in *Proc. PAC'99*, New York, NY, USA, Mar. 1999, paper FRA56, pp. 3510–3512.

[4] C. Adolphsen *et al.*, "Processing Studies of X-Band Accelerator Structures at the NLCTA", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper ROAA003, pp. 478–480.

[5] Robin Rajamaki. "Vacuum arc localization in CLIC prototype radio frequency accelerating structures", Master's thesis, Aalto University, Aalto, Finland, 2016.

[6] J. Frisch *et al.*, "Studies of Breakdown in High Gradient X-Band Accelerator Structures Using Acoustic Emission", in *Proc. LINAC'02*, Gyeongju, Korea, Aug. 2002, paper TH484, pp. 788–790.

[7] F. Le Pimpec. "Limitations on the use of acoustic sensors in RF breakdown localization", SLAC National Accelerator La-boratory, Menlo Park, CA, USA, Rep. SLAC-TN-04-049, 2004.

[8] F. Le Pimpec *et al.*, "An Acoustic Sensor System for Localizing RF Breakdown in Warm Copper Accelerating Structures", *Nucl. Instrum. Meth. A*, vol. 582, pp. 345–355, 2007.