CAPTURING BEAM FROM TWO DIFFERENT LINEAR ACCELERATORS IN THE CANADIAN LIGHT SOURCE BOOSTER SYNCHROTRON

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Abstract

The Canadian Light Source recently replaced its aging linear accelerator (linac) with one procured from Research Instruments GmbH (RI). The original linac operated at a frequency of 2856 MHz, which is not a harmonic of the 500 MHz booster ring rf. The two rf systems were not synchronized and the linac beam was rebunched into the booster rf buckets, causing losses of at least 33% at injection. The RI linac is synchronized to the booster ring rf frequency through the 500 MHz pulsed gun and sub-harmonic pre-buncher. The RI linac S-band rf is also synchronized and operates at approximately 3.0 GHz, the sixth harmonic of the booster ring rf frequency.

In this report, we compare observations made while capturing the beams from these two linacs with different rf frequencies.

INTRODUCTION

The Canadian Light Source (CLS) uses a linear accelerator (linac) to accelerate electrons to the injection energy of the booster synchrotron. The linac was recently replaced, and this provided an opportunity to compare capturing the two different linac beams. The original linac operated at 2856 MHz and was unsynchronized with the booster rf. The replacement linac operates at 3.0 GHz and uses a sub-harmonic pre-buncher (SPB) operating at the booster rf frequency, 500 MHz, to provide synchronization.

LINAC COMPARISON

Table 1 compares a number of features of the two linacs. The 2856 MHz linac was designed for the nuclear physics program at the Saskatchewan Accelerator Laboratory (SAL) and was repurposed for the CLS injection system. It had a maximum energy of 300 MeV [1] but was operated at 250 MeV to improve reliability for feeding the booster ring. The electron source output a continuous pulse that was bunched into buckets spaced by 350 ps.

The 3.0 GHz linac was manufactured by Research Instruments GmbH (RI) as a replacement for the aging 2856 MHz linac. We describe the relevant history in another proceeding at this conference [2]. The 3.0 GHz linac SPB operates at 500 MHz to get a bunch spacing of 2.0 ns.

CLS staff performed quadrupole scans [3, pp. 226] using a focusing quadrupole, a defocusing quadrupole and a view screen to measure the emittances [4, 5]. The quadrupole scans occurred on April of 2024 for the 2856 MHz linac and October of 2025 for the 3.0 GHz linac. The analysis used a

Table 1: Comparison between the Two Linacs

Quantity	**Unit**	**2856 MHz linac**	**3.0 GHz linac**
Frequency	MHz	2856	3000.3
Bunch spacing	ps	350	2000
Design energy	MeV	300	250
Operating energy	MeV	250	152
ϵ_{Nx}	mm mrad	2.3	58.1
ϵ_{Ny}	mm mrad	88.7	56.0
Energy st. dev.	%	0.15	0.17
Energy FWHM	%	0.14	0.20
Energy FWQM	%	0.26	0.31

thick-lens model of the quadrupoles and all emittance data sets were analyzed together using the same software. We show the fitting for the vertical emittance for both linacs in Fig. 1, and all emittance results are listed in Table 1. We use the symbol ϵ_{Nx} for the horizontal normalized emittance and ϵ_{Ny} for the vertical normalized emittance.

The horizontal and vertical normalized emittance values for the 3.0 GHz linac are symmetric and near the expected 50 mm mrad [6]. However, the normalized horizontal and vertical emittance values for the 2856 MHz linac differ significantly from each other. They also different form the historic value of 0.3 mm mrad [1]. It is not known if this disagreement is due to the linac setup or measurement setup and, as the linac has been disassembled, we will not be able to investigate further.

The offset vertices of the curves in Fig. 1 show that the vertical betatron functions from the two linacs were different

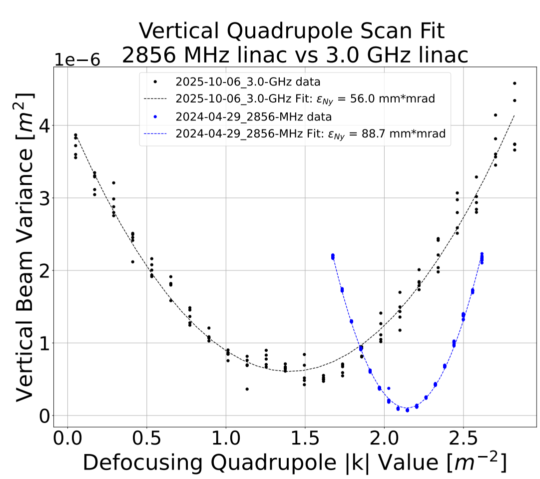

Figure 1: Quadrupole scan measurements used to find the normalized vertical emittances for the two linacs. Figure adapted from [5, Fig. 25].

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at the time of measurement. The betatron function and its derivative can be adjusted using quadrupole magnets within and external to the linacs.

We measured the energy spreads using a view screen in a dispersive region, as described in [2]. The values for the 3.0 GHz linac in Table 1 come from [2, Fig. 2]. The energy spread measurement for the 2856 MHz linac was done in April of 2024 whereas the measurement for the 3.0 GHz linac was done in October of 2025. We report the standard deviation (st. dev.), full width at half maximum (FWHM) and full width at quarter maximum (FWQM) for both linacs in Table 1.

LONGITUDINAL PHASE SPACE

Both linacs operate in the S-band and their bunches were captured by the 500 MHz booster rf. Figure 2 shows six S-band linac bunches within one 2 ns booster rf bucket calculated using the electron tracking software `elegant` [7].

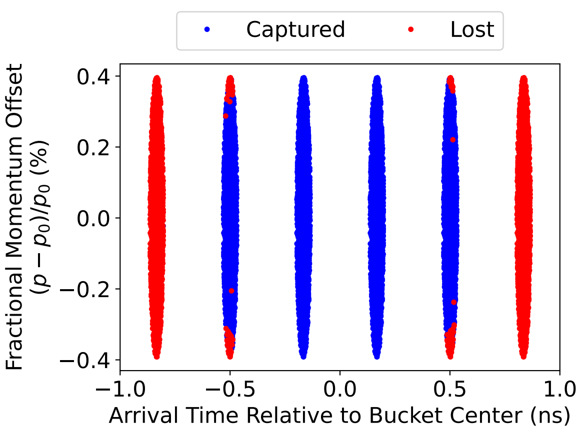

Figure 2: Longitudinal phase space from a tracking simulation showing six S-band linac bunches within one 2 ns booster bucket. The inner two bunches arrive near the booster bucket's stable fixed point and are captured. The outer two bunches arrive near the booster bucket's unstable fix point and are lost. The remaining two bunches are captured as long as their energy spread is not too large.

The 2856 MHz linac bunches were unsynchronized with the booster ring 500 MHz, and their arrival time was random. In the simulation example shown in Fig. 2 we would expect four of the six S-band buckets to be captured for the energy spreads measured in Table 1. We used fast current transformers (FCTs) to measure the charge into the booster and a parametric current transformer (PCT) to measure the captured charge. When the injection system was fully optimized with the 2856 MHz linac, our maximum capture efficiency was about 67%, which aligns with the simulation interpretation.

The 3.0 GHz linac uses an SPB to fill only one of every six S-band buckets when all linac phases are optimized. As the SPB is synchronized to the booster rf, we can ensure that the electrons arrive in the center of the booster rf bucket. In principle this should allow us to capture with near 100% efficiency. However, we have not yet been able to realize this due to the low operating energy of the linac [5]. Efforts are underway to improve the booster capture efficiency [2].

MEASUREMENT OF THE SYNCHROTRON FREQUENCY

We used horizontal data from a turn-by-turn beam position monitor (BPM) in a dispersive region of the booster to measure the synchrotron frequency. We plot two such measurements in Fig. 3.

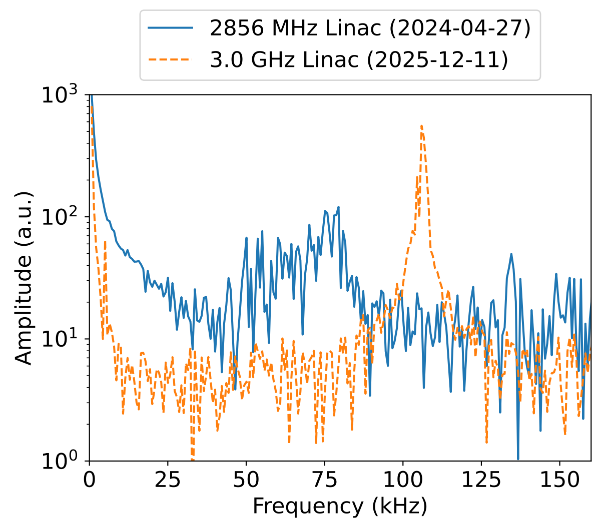

Figure 3: Synchrotron frequency comparison from horizontal turn-by-turn BPM data in a dispersive location measured at the beginning of the booster ramp. The peak frequency for the 3.0 GHz linac is 106 kHz and the structure for the 2856 MHz linac extends from about 30 to 88 kHz. As the synchrotron frequency is proportional to the inverse square root of energy [3, pp. 264], the higher synchrotron frequency for the 3.0 GHz linac is explained by its lower beam energy.

The synchronized, 3.0 GHz linac beam produces a clear, sharp synchrotron frequency peak. If an electron bunch from this linac were to arrive perfectly on-energy and on-phase with the booster rf, its centroid would not undergo synchrotron motion. We made use of this observation to optimize the energy matching between the linac output and the booster dipole magnets, and the phase matching between the linac SPB and the booster rf. We measured the amplitude of the synchrotron frequency peak and minimized it while adjusting accelerator systems to improve matching.

At injection time, the unsynchronized 2856 MHz linac beam produced a broad synchrotron frequency peak. That broad peak became sharply pointed as the beam began to damp, at about 100 ms into the 598 ms ramp. The broad peak from the unsynchronized linac beam was less useful than the sharp, clear peak from the synchronized linac beam for study and optimization of booster capture.

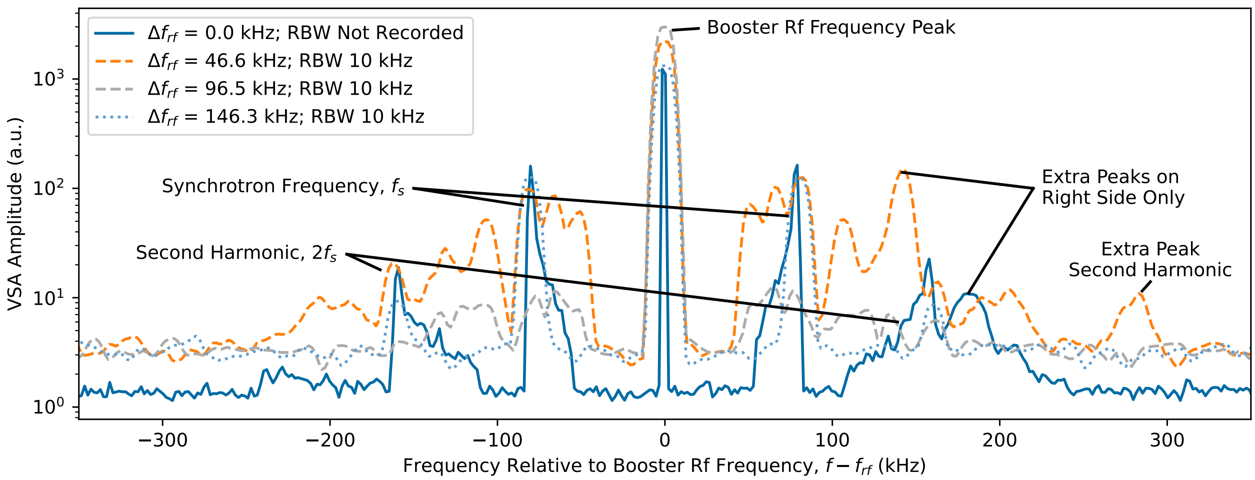

Figure 4: Using the unsynchronized 2856 MeV linac in January of 2024, we measured the beam frequency spectrum at the beginning of the booster ramp for four different booster rf frequencies. The measurement used a vector signal analyzer (VSA) connected to a stripline beam position monitor with all four strips summed. The center spike is the booster rf frequency, f_{rf} = 500.0472, 500.0938, 500.1437 or 500.1935 MHz (Δf_{rf} = 0, 46.6, 96.5 or 146.3 kHz). We unfortunately did not record the VSA resolution bandwidth (RBW) for the measurement at the nominal booster rf frequency, $\Delta f_{rf} = 0$. For the measurements at non-zero Δf_{rf}, we reduced the VSA resolution in order to better observe the extra peak in the Δf_{rf} = 46.6 kHz data and search for it in the Δf_{rf} = 96.5 and 146.3 kHz data.

UNSYNCHRONIZED RF SYSTEMS

Having the linac and booster ring rf systems unsynchronized allows for measurements that cannot be made with synchronized systems. The booster ring cavities were able to tune over a wide range of frequencies and we were able to shift the booster ring rf frequency by 146.3 kHz during a dedicated studies shift[1].

The beam spectrum measurement of Fig. 4 shows the $f_{rf} \approx 500$ MHz rf peak in the center, with broad synchrotron frequency peaks in the 50-85 kHz range on either side. Beyond those, we see second harmonics of the synchrotron frequency in the 100-170 kHz range on either side of the central peak.

There is an extra peak observed in the $\Delta f_{rf} = 0$ and 46.6 kHz data which appears only on the positive side of the central peak and not on the negative. This extra peak does not change absolute frequency when the booster ring rf frequency changes (it moved in Fig. 4 only because the central peak frequency moved by Δf_{rf} = 46.6 kHz) and is fixed at around 500.23 MHz. The extra peak is only present at injection time and disappears by 10 ms into the 598 ms ramp. It can also be made to disappear by increasing the amplitude of the rf at injection time. We hypothesize that the extra peak is due to a known systematic inboard misalignment of the booster ring magnets, but we are not able to make a firm conclusion.

[1] The storage ring rf had to be turned off for this measurement as this frequency shift is far more than the storage ring rf system can manage and the two share a common master oscillator.

DISCUSSION

Having had two different linacs feed the same booster synchrotron presented an opportunity for study. The largest conceptual difference in capturing the two different beams was that the 2856 MHz linac was unsynchronized from the booster rf while the 3.0 GHz linac and its SPB were synchronized. Both approaches have their merits. The theoretical capture efficiency of the 3.0 GHz linac is very high and the synchrotron tune peak can be used to optimize accelerator parameters. However, at CLS, the storage ring, booster ring and linac now share a common master oscillator. The storage ring orbit control system adjusts the master oscillator frequency in order to control dispersion as the ring circumference varies. It now also varies the linac rf frequency, which significantly complicates linac operations. In practice, it is better to have the linac and storage ring rf frequencies uncoupled, either by rebunching in the booster, time varying the rf frequency in the booster [8], a more sophisticated synchronization system [9], a chopper [10] or by other means.

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