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RECOMMISSIONING OF THE CANADIAN LIGHT SOURCE BOOSTER SYNCHROTRON

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Abstract

The Canadian Light Source booster synchrotron was originally commissioned in 2002 and has worked reliably for many years. However, the operating point was not the design operating point and the booster suffered from poor quantum lifetime at the extraction energy. The low quantum lifetime caused current loss of approximately 25% in the milliseconds before extraction. We have recommissioned the booster using the design optics, and the current loss before extraction is now only 6%. In this paper, we discuss the measurements and simulations involved in our recommissioning work.

INTRODUCTION

The Canadian Light Source (CLS) uses a booster synchrotron to accelerate the 250 MeV beam output by the linac to the storage ring energy of 2.9 GeV [1]. The booster was originally commissioned in 2002 [2]. Instead of the design tunes of (5.18, 2.38), the commissioning team used the tunes of (4.81, 2.78). We successfully used this operating point for many years, but the approximately 25% current loss at extraction due to reduced quantum lifetime was undesirable. Figure 1 shows the loss of current near the extraction energy. While the tunes take a wandering path and cross twice during the ramp, tune behavior does not appear to be correlated with particle loss.

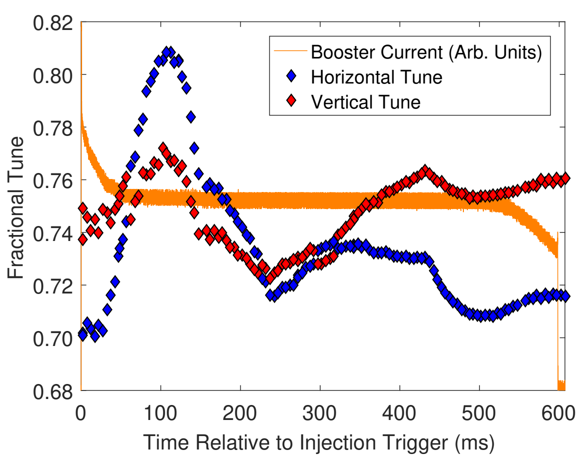

Figure 1: Measured tune drift over the ramp plotted with the measured current profile with the original commissioning optics.

In 2017 we disassembled the booster extraction area to allow a 4 m long, double elliptically polarizing undulator [3] to be moved from the magnetic measurement facility to the storage ring tunnel. We decided to recommission the booster synchrotron using optics similar to the design optics. The most significant technical difference between the 2002 commissioning and the 2017 recommissioning is that we were able to make use of Libera Brilliance turn-by-turn BPMs and a synchrotron light monitor in 2017.

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Table 1: Parameters for calculating quantum lifetime for the CLS booster synchrotron with their values at an electron energy of $E = 2.9$ GeV.

Parameter	Symbol	Value
Momentum Compaction Factor	α_c	0.617
Energy Loss Per Turn	U_0	862 keV
Energy Spread	σ_E	2.68 MeV
Longitudinal Damping Time	τ_E	1.16 ms
Harmonic Number	h	171
Accelerating Voltage	V_{rf}	1.75 MV

QUANTUM LIFETIME

Quantum lifetime is a single-particle effect due to the stochastic emission of synchrotron radiation. Sometimes an electron may emit enough radiation that it finds itself outside the energy acceptance of the accelerator. The quantum lifetime can be calculated using [4, 5]

$$\tau_q = \frac{1}{2}\tau_E \frac{e^{\xi}}{\xi}, \tag{1}$$

where

$$\xi \equiv \frac{\epsilon_{max}^2}{2\sigma_E^2} \tag{2}$$

relies on the energy distribution and maximum acceptance of the rf via

$$\epsilon_{max}^2 = \frac{U_0 E}{\pi \alpha_c h} F\left(\frac{eV_{rf}}{U_0}\right), \tag{3}$$

where

$$F(q) \equiv 2\left[\sqrt{q^2 - 1} - \arccos\left(\frac{1}{q}\right)\right], \tag{4}$$

and the meanings and values of these parameters can be found in Table 1.

Many of these quantities are dependent on the electron energy and the quantum lifetime itself has a significant dependence on energy.

The two quantities that we have the most control over are α_c and V_{rf}. While we are not able to increase V_{rf} due to the

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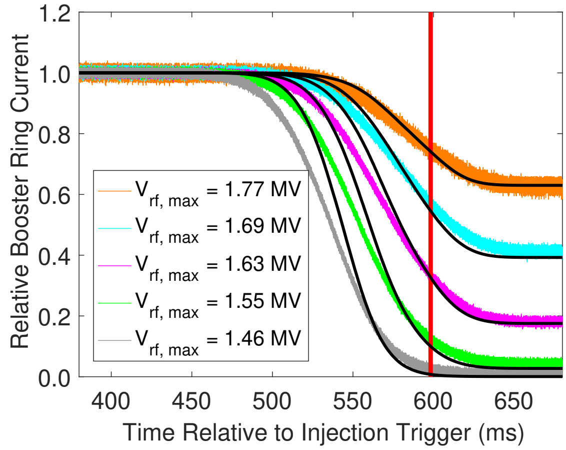

Figure 2: Comparison of measured booster current (colored data) with calculations based on quantum lifetime (black curves) for various $V_{rf,max}$ with the extraction time marked with a red line.

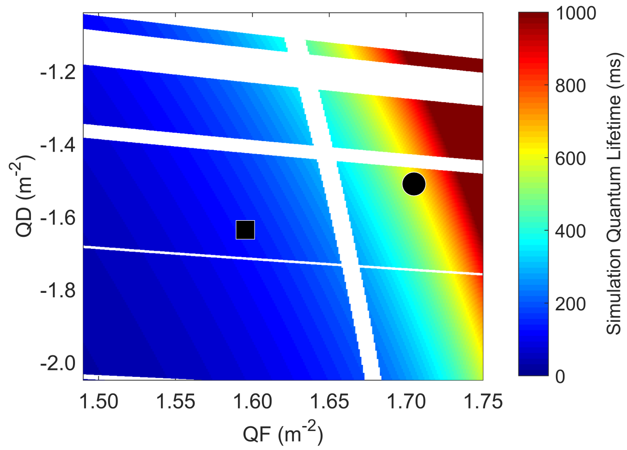

Figure 3: Simulation quantum lifetime for a quadrupole scan at 2.9 GeV with V_{rf} = 1.75 MV. The commissioning optics are marked with a black square and the design optics are marked with a black circle.

limitations of the amplifier, we can decrease it to demonstrate understanding of the issue. In Fig. 2 we show the current over the booster ramp with several $V_{rf,max}$ values. V_{rf} is ramped over the booster cycle and $V_{rf,max}$ is its maximum value at extraction time. The only fit parameter used to calculate quantum lifetime is the calibration of the cavity probe to peak rf voltage, which we found to be of 8.55 MV/mV. Overall the calculated curves fit the measured data reasonably well and we can be convinced that the observed losses are indeed due to quantum lifetime.

We can also look at how varying α_c impacts the quantum lifetime. Since α_c is dependent on the linear optics and we have two families of quadrupole magnets, we perform a quadrupole scan of all linear stable settings [6, 7] using the elegant optics code [8] and calculate the quantum lifetime for each candidate operating point. We plot the quadrupole scan in Fig. 3. The quantum lifetime for the design optics is clearly higher than the commissioning optics. There may be operating points with even higher quantum lifetime, but simulations using a seemingly promising candidate calculate zero dynamic aperture when lattice misalignments are included in the model.

As a result of these measurements and simulations, we decided to recommission the booster synchrotron using tunes near the design optics.

RECOMMISSIONING

Ultimately, we chose tunes (5.26, 5.22) for injection and (5.28, 5.22) for extraction, which have the same integer tune and are in the same quadrant as the design tunes. Immediately we see that the quantum lifetime has improved, as shown in Fig. 4.

With the advantage of turn-by-turn BPM electronics, we were able to more easily measure and adjust the tunes over the ramp with the final result shown in Fig. 5.

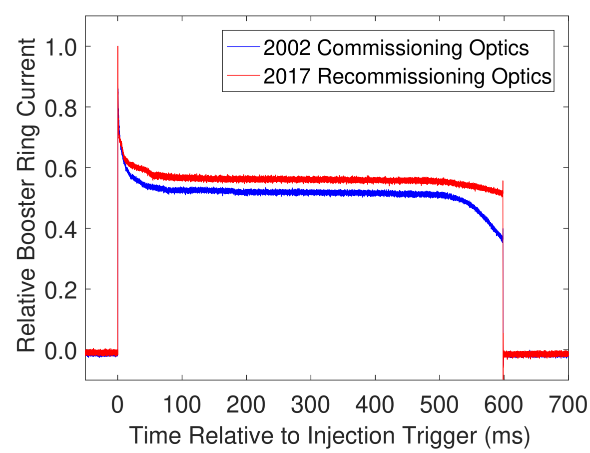

Figure 4: Current profiles over one booster ramp showing the approximately 6% current loss at extraction energy with the recommissioned optics, which are similar to the design optics, compared with the approximately 25% current loss with the original commissioning optics.

The initial current loss is believed to be due to the rebunching of the 2856 MHz linac beam in the 500 MHz booster. After the intial losses, the current profile remains flat until we are close to the extraction energy. The tunes drift during the ramp, but this drift does not appear to be connected to particle loss, so it is acceptable. As we reach the extraction energy, we see a small drop in the current due to quantum lifetime.

We resolved the ν v.s. $1 - \nu$ tune degeneracy by varying the strength of the quadrupoles. For instance, when the strength of horizontally focusing quadrupoles increases, the horizontal tune increases and the vertical tune decreases, implying that we are in the correct quadrant and the fractional tunes at extraction are (0.28, 0.22) and not (0.72, 0.78).

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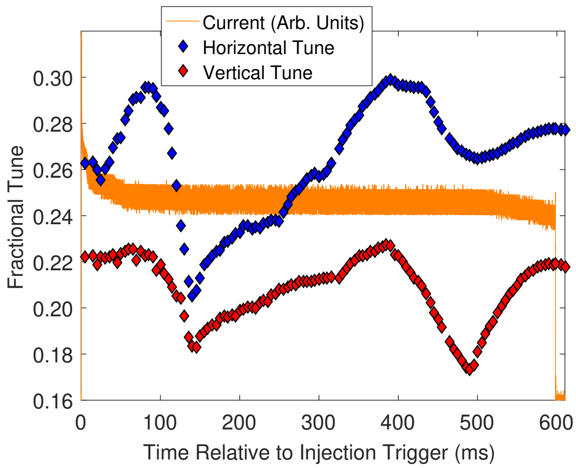

Figure 5: Measured tune drift over the ramp plotted with the measured current profile after recommissioning.

Measuring the integer portion tune with only 8 BPMs can be difficult. We are left to assume that we have the correct integer portion because the quantum lifetime improved as expected and the integer portion was measured reliably during the initial commissioning using 28 analog BPMs [2].

We added a synchrotron light monitor to the booster for the recommissioning effort. The monitor is a simple design using a prism to reflect the light and a lens to focus it onto a Spiricon Gig-E CCD camera which uses the Spiricon BeamGage software for readout and analysis. The prism is damaged by radiation, but the lifetime is long enough that we were able to use a single prism for the recommissioning. This camera was useful in diagnosing problems that arose during the recommissioning. Images of the beam at the injection and extraction energies are shown in Fig. 6.

According to the simulations, we also expect a modest drop in horizontal emittance from 596 nm to 550 nm. However, we have not been able to realize an improvement in injection efficiency due to this small decrease in emittance.

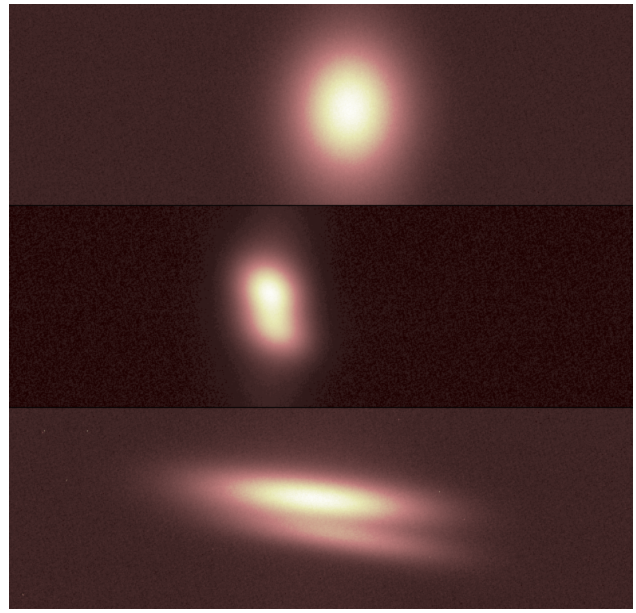

Figure 6: Observation of the booster beam using the synchrotron light monitor at 25 µs after injection (top), 220 ms after injection (middle) and 592 ms after injection (bottom), which is the time of extraction. The vertical distortion to the middle image and the artifact in the bottom image are believed to be due to radiation damage to the prism.

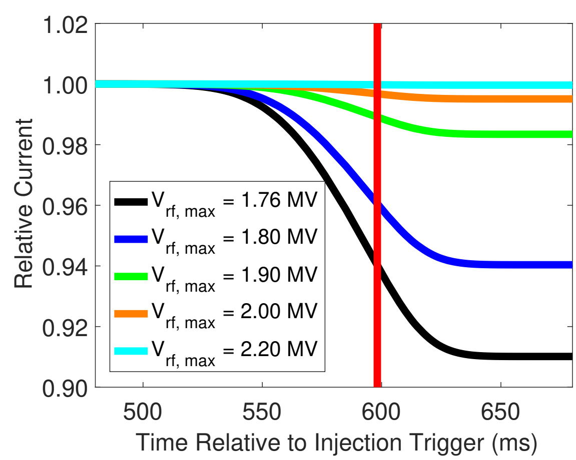

Figure 7: Comparison of simulated booster current profiles with increased $V_{rf,max}$ with the extraction time marked with a red line.

AMPLIFIER REPLACEMENT

Since the recommissioning of the booster ring, we have begun an amplifier replacement project. The amplifier replacement is primarily motivated by the obsolete klystron used in the booster rf amplfier, but it also provides us with an opportunity to further improve booster operation. The new amplifier will be a solid state amplifier built by Cryoelectra GmbH with more power than the existing klystron amplifier. As such, we will be able to increase the accelerating voltage at the extraction energy and further increase the quantum lifetime. The expected effect of increased voltages on the booster current profile is shown in Fig. 7. These calculations are done with the recommissioned optics, which are similar to the design optics.

CONCLUSION

We have discussed the recommissioning of the CLS booster synchrotron that was performed in 2017. The original commissioning optics, used since 2002, were not optimal due to the low quantum lifetime causing approximately 25% current loss at extraction. By switching to an operating point close to the design operating point, we reduced these losses to 6%. An upgrade of the booster rf amplifier will further reduce these losses.

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