ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-MOP037

TUNE FEEDBACK AT THE CANADIAN LIGHT SOURCE

W. A. Wurtz*, C. K. Baribeau, A. M. Duffy
Canadian Light Source, Saskatoon, Saskatchewan, Canada

Abstract

In order to maintain good injection efficiency for top-up operation at the Canadian Light Source, we must keep the betatron tunes constant even as changes in insertion device fields cause the tunes to vary. To meet this requirement, we implemented a tune feedback system. We measure the tunes at a rate of 1 Hz using Dimtel bunch-by-bunch systems. The transverse feedback function of the bunch-by-bunch systems provides tune measurements without disturbing the electron beam. We adjust two quadrupole families at a rate of 0.25 Hz to control the horizontal and vertical tunes. In this article we describe the tune feedback system, its development and its performance. The system has proven to be very robust, enabling reliable top-up operation.

INTRODUCTION

The Canadian Light Source (CLS) began operating in top-up mode for user operations in 2021. In top-up mode, charge is injected into the storage ring every few minutes to maintain a constant current with the present target being between 219 and 220 mA. Top-up requires reliable and efficient injection, and the tune feedback application is an important part of our top-up implementation. We developed the tune feedback application in an iterative manner, incorporating feedback from operators and subject matter experts. Through each iteration we identified operational issues, implemented corrections or new features to resolve the issues, tested the new features and their interactions with existing features and deployed the new version. The resulting product can gracefully handle a variety of situations and provides an alarm and diagnostic information for the operators. The algorithm is adjustable for machine studies outside of user mode, or to implement workarounds while we resolve issues with external systems. Overall, the tune feedback application has been successful and top-up operation has been reliable.

TUNE AND INJECTION

For top-up mode, we desire that >90% of the charge injected into the storage ring be captured. We measure the stage 2 injection efficiency using an integrating current transformer (ICT) at the end of the transfer line and the parametric current transformer (PCT) in the storage ring. Because there is some uncertainty in the ICT calibration, we give the stage 2 injection efficiency in arbitrary units (a.u.) with a stage 2 efficiency of 97 a.u. meaning that somewhere between 94 and 100% of the electrons were captured.

We have previously reported on injection efficiency issues caused by a superconducting wiggler, BMIT SCW4 [1], and an elliptically polarizing undulator, SM EPU75 [2]. We show updated injection efficiency tune scans for these devices in Fig. 1. The nominal tunes, represented by a diamond marker, are 10.242 for the horizontal and 4.290 for the vertical. We see that the nominal tunes are on a small island of good injection efficiency, and if the tunes were to shift, the stage 2 efficiency would quickly become unacceptable. Tune shifts are mostly caused by insertion device field changes.

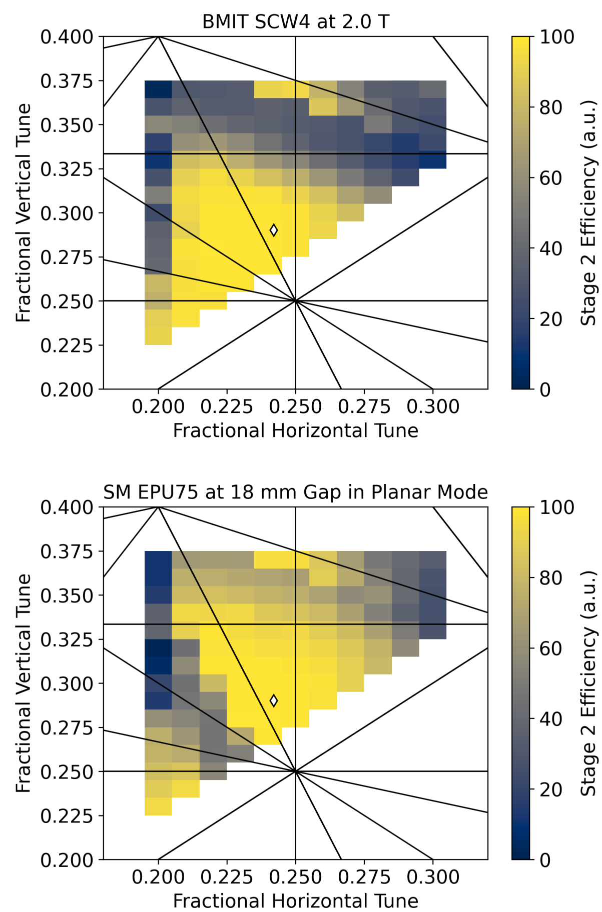

Figure 1: Measurements of injection efficiency as a function of the fractional tunes for two insertion devices with all other insertion devices forced open or turned off. We operated the BMIT SCW4 at approximately half its maximum field in order to avoid quenching the device during the measurement.

We do not measure the integer portions of the tunes during normal operations and obtain the fractional portions by performing a Fourier transform of position data. In this work, if we say that the horizontal tune is 0.242, the integer portion is understood to be 10, and similar for the vertical with an integer portion of 4.

* ward.wurtz@lightsource.ca

ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-MOP037

DEVELOPMENT

The tune feedback application began with a simple script written by an accelerator physicist in Python using PyEpics [3]. While it was able to control the tunes during an eight hour machine development shift, it was far from being the robust tool that we needed for reliable operation in user mode.

The script was given to a system analyst and we began developing it into a useful application, taking an approach heavily influenced by flow-based agile [4]. The product vision was for a robust application that would function with essentially 100% uptime and would be easy for the operators to use. For each iteration, we created a backlog of features, ranked them in priority, and implemented them. The CLS machine schedule provides a maintenance shift every week, which allowed us to test our software without beam. If the test was successful, we would then schedule a dedicated shift for online testing with beam. The results from each test informed our revisions to the backlog of features for the next iteration.

As soon as we had a version that was robust enough to survive our attempts to make it fail, we called this version the minimum viable product and began running it in normal operations. We quickly built a new backlog using feedback from our operators and our own observations of how the system functioned in the real environment. We continued to iterate, first quickly, then more slowly until we had a robust application with the features necessary to survive all the cases that it encountered in user and machine studies modes of operations.

The iterative process was essential for this project, and we could not have been successful with a traditional/waterfall approach. With a system as complex and dynamic as a storage ring, there was no way for us to foresee all the features that were needed to make the tune feedback application robust.

THE TUNE FEEDBACK SYSTEM

Figure 2 shows the tune feedback system expert panel. The data and controls displayed on this panel are the result of several development iterations. Grayed fields can only be changed while the tune feedback loop is open.

The CLS storage ring uses Dimtel iGp12 bunch-by-bunch systems [5] for transverse feedback and other bunch-by-bunch applications. When transverse feedback is running, the averaged bunch spectra from these systems contain notches at the tune frequencies due to the negative feedback loop [6, 7]. These notches have proven to be robust measurements of the fractional betatron tunes. The plots 'TFC:2405-101:X:SRAM:SPEC' and 'TFC:2405-102:Y:SRAM:SPEC' in Fig. 2 show example spectral data with notches at the horizontal and vertical tunes, respectively.

We input the CLS injection timing trigger, which has a constant rate of 1 Hz whether we are injecting or not, to the bunch-by-bunch system. The bunch-by-bunch system captures the data to calculate the notched spectra before the trigger. Without this deliberate choice of timing, the injection transient caused when the kickers do trigger would obscure the notches.

There are a variety of circumstances where we require the tune feedback application to cease adjustments to the quadrupoles, such as when the betatron tunes cannot be accurately measured. We have codified these circumstances with a signal status, where the application will only adjust quadrupole settings when the signal status is deemed GOOD. The circumstances that render the signal status anything other than GOOD are configurable in the application's expert panel, however, we permit most settings to be adjusted only when the feedback loop is open.

The notch is always negative in the spectral waveforms and we require that it crosses a threshold, represented by the horizontal lines in the plots. The threshold is determined by calculating the standard deviation of the waveform in a region away from the notch, then multiplying the standard deviation by a user defined number, which is 10.0 in Fig. 2 for both the horizontal and vertical. If the notch does not cross the threshold, which occurs if the stored beam is lost or if the stored current is too low, then the signal is declared LOW and the tune feedback loop will open after a user specified number of attempts, which is set to 3 in Fig. 2.

If a vacuum transient occurred in the storage ring, or if a trigger was misconfigured such that the injection transient appeared in the spectral waveforms, then the waveforms would be positive going, obscuring the notch. To handle this situation we calculate the skewness of the waveforms,

$$g_1 \equiv \frac{m_3}{s^3} \quad (1)$$

where s is the sample standard deviation and

$$m_3 \equiv \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^3 \quad (2)$$

is the third central moment of the waveform data, x_i with sample mean $\bar{x}$. Skewness is a dimensionless number that is easy to understand intuitively; it tells us whether, and by how much, the distribution is skewed positive or negative.

The application has a user defined maximum skewness threshold, set to 0.0 in Fig. 2 for both horizontal and vertical. If the skewness is above this threshold, the signal is declared BAD and the tune feedback loop will open after a given number of attempted tune measurements, which is set to 15 in Fig. 2.

If the application does not receive fresh data from the bunch-by-bunch system in a given number of seconds, set to 10.0 s in Fig. 2, the signal is declared TIMEOUT and the tune feedback loop will open.

In normal conditions, for the signal to have status GOOD and allow the tune feedback loop to be closed, the notch must be large, the skewness must be negative and the waveforms from the bunch-by-bunch system must be updating.

If we lose the beam in the storage ring, the tune feedback loop opens because the signal goes LOW. It might also be

ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-MOP037

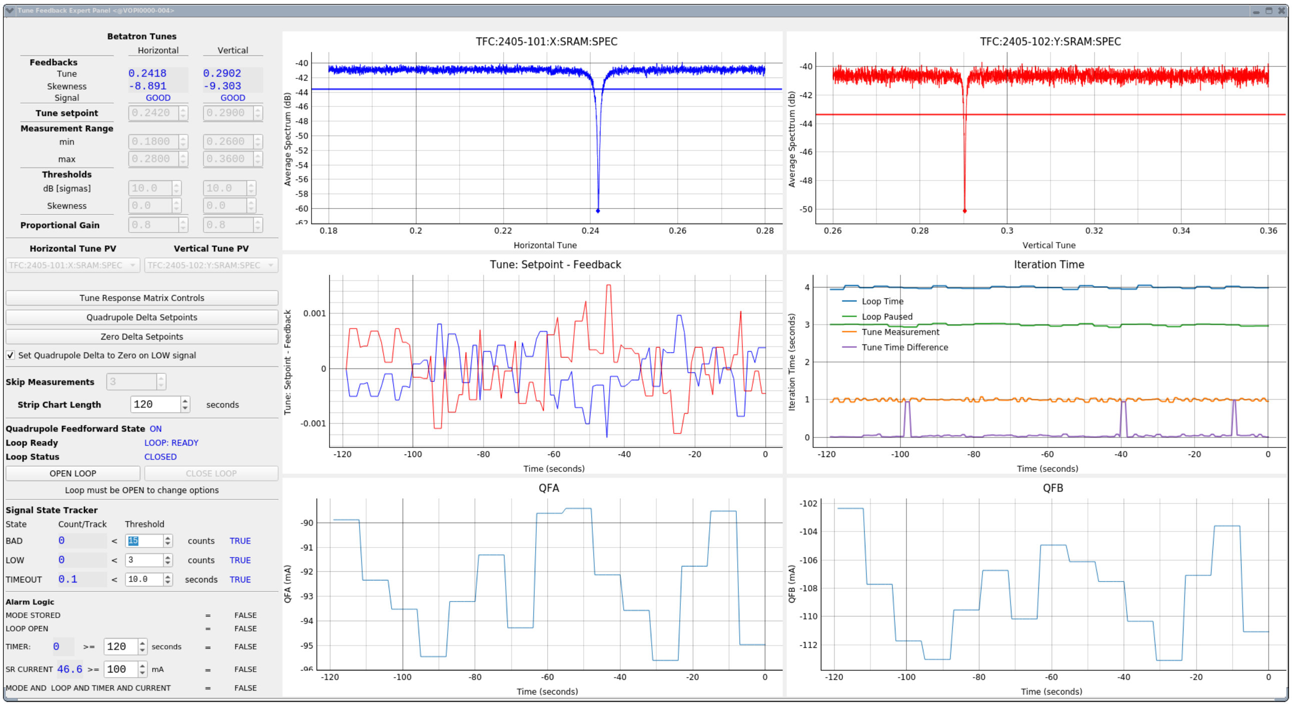

Figure 2: Tune feedback system expert panel.

BAD, but we have specified that LOW will take priority over BAD. After the signal goes LOW, what should the quadrupole set points do? Through testing and experience, we found that we usually want to set the quadrupoles to their default settings, zeroing any offsets that tune feedback has applied. This makes it easier for the operators to perform the recovery injection, when many insertion device gaps are opened. However, for some machine studies activities, we want the opposite behaviour, with the quadrupole values staying unchanged when we intentionally dump the beam. The checkbox 'Set Quadrupole Delta to Zero on LOW signal' on Fig. 2 allows the operator to set the desired behaviour.

For signals that are BAD but not LOW, the tune feedback application does not set the quadrupoles to their default values, and this is a choice based on experience. A BAD signal usually means a vacuum transient is occurring in the storage ring. The desired behaviour is for tune feedback to pause during a short transient, and resume after it passes.

The nominal tune feedback configuration settings are conservative to ensure that the application does not attempt to correct the tunes using questionable data. If there is an issue with the signals from the bunch-by-bunch system, there are many degrees of freedom to adjust in order to keep tune feedback operating. For example, we replaced a failed component external to the bunch-by-bunch system and this caused a slight timing change for an incoming signal. This resulted in notches that were not optimal with some positive going structure and small signals. We were able to adjust the tune feedback application options in order to run with the distorted notches until the bunch-by-bunch system was reoptimized for the shifted timing.

Once we have the tune measurements, we can use two quadrupole families to adjust them. We use the QFA and QFB quadrupole families, which are the two quadrupole families between the ends of the straight sections and the dipoles in the double bend acromats, as shown in Fig. 3. For the CLS storage ring, all of the vertical focusing is done in the dipoles, so there are no vertically focusing quadrupoles. We are able to use two horizontal focusing quadrupoles because the horizontal and vertical betatron functions are very different at these quadrupole locations. The quadrupoles can be adjusted together to control one tune without varying the other.

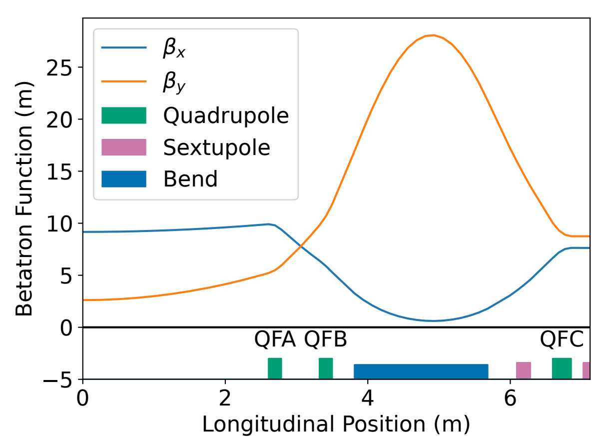

Figure 3: Betatron functions for one half of a double bend acromat cell.

As we are treating quadrupoles as families, we are performing a global tune correction, not a local correction. The tune feedback application outputs settings to a Quadrupole Feedforward application, which applies offsets to the quadrupole settings without overwriting the nominal settings.

The tune feedback application can measure a 2x2 response matrix by varying the two quadrupole families and measuring the tune shifts. It then inverts the response matrix to determine the necessary change in quadrupole settings to shift the tunes toward the desired setpoints. This is a simple proportional loop and the application includes proportional gains, which are set to 0.8 in Fig. 2. The plot 'Tune: Setpoint - Feedback' in Fig. 2 shows that, as the tunes vary due to noise in magnet power supplies and insertion device motion, the tune feedback application brings the difference toward zero.

The quadrupole power supplies date from the original installation of the storage ring and the design is over 20 years old. They are not intended to be updated quickly and we find that updating them at 0.25 Hz works well. The tune data update at a rate of 1 Hz and the tune feedback application simply skips a number of tune measurements, set to 3 in Fig. 2. The 'Iteration Time' plot in Fig. 2 shows the time to take a tune measurement, the pause when skipping measurements and the total loop time. The 'Tune Time Difference', which should ideally be zero, is not always so; this is a complex timing issue stemming from how we get the information from the bunch-by-bunch system. We chose not to resolve this issue as it would have required substantial investigation time for no practical benefit.

The tune feedback application generates an alarm to tell the operators if the loop is open when it should be closed. The logic developed over several iterations as we worked to suppress nuisance alarms. For modes other than user operations (mode: STORED), tune feedback is not required. If we are delivering low current for beamline conditioning, the signals from the bunch-by-bunch system may not be sufficiently strong, so we don't use tune feedback. After an injection, completing the procedure requires a number of seconds between the operator switching to STORED mode and closing the tune feedback loop; the alarm is suppressed after entering STORED mode for a short time, set to 120 s in Fig. 2. Using this logic, nuisance alarms have been suppressed; if the tune feedback alarm appears in the alarm handler, then there is a real problem. For example, a recent vacuum issue in the storage ring caused a number of tune feedback alarms because the loop was opening when a vacuum transient would cause the signal to be BAD for more than 15 tune measurements. The tune feedback application functioned as designed and the failed vacuum component was identified and replaced.

While the expert panel of Fig. 2 contains many useful features, the operators rarely need to adjust them. Figure 4 shows a very simple GUI, which presents the most important information, allows the operators to turn the systems on and off, and provides access to the expert panel.

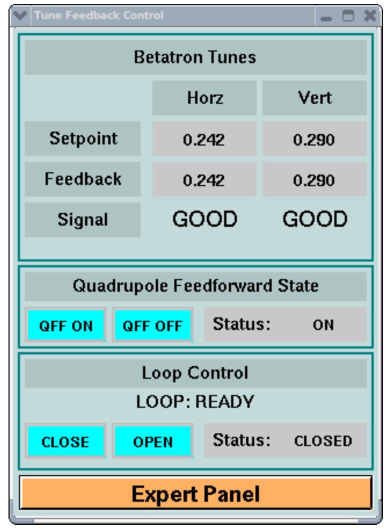

Figure 4: Tune feedback operator controls.

CONCLUSION

When CLS moved from decay mode operation to top-up, we received a very positive response from the user community. With an eclectic mix of insertion devices, the horizontal and vertical tunes will vary as insertion device setpoints are changed. The tune feedback system has been essential for maintaining good injection efficiency in this dynamic environment. The final product is the result of several development iterations and input from many individuals.

ACKNOWLEDGMENTS

We would like to thank D. Teytelman (Dimtel), T. Batten (CLS) and J. Vogt (CLS) for implementing and maintaining the bunch-by-bunch system and teaching us how to use it.

The Canadian Light Source receives funding form 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] W. A. Wurtz, L. O. Dallin, and M. J. Sigrist, "Beam Based Measurements with Superconducting Wigglers at the Canadian Light Source with Applications to Nonlinear Beam Dynamics", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper TUPPP001, pp. 1599–1601.

[2] W. A. Wurtz, C. K. Baribeau, and M. J. Sigrist, "Rectifying unexpected injection issues due to an elliptically polarizing undulator", *Nucl. Instr. and Meth. A*, vol. 1048, p. 168001, 2023. `doi:10.1016/j.nima.2022.168001`

[3] The PyEpics Collaboration, `https://pyepics.github.io/pyepics/index.html`

[4] Project Management Institute and Agile Alliance, *Agile Practical Guide*, pp. 24-25, Project Management Institute Inc., 2017.

[5] Dimtel, San Jose, USA. `http://www.dimtel.com`

ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-MOP037

[6] D. Teytelman, *iGp12-285F Signal Processor Technical User Manual*, Rev 2.15, 2019.

[7] D. Teytelman, "Experience with feedback systems in modern synchrotron light sources", presented at the Accelerator Performance and Concepts Workshop, Frankfurt, Dec. 2018. https://indico.gsi.de/event/7510/contributions/33547/attachments/24263/30374/dt_feedback_apec_20181211.pdf