

# EMITTANCE MEASUREMENTS IN THE BTS TRANSFER LINE AT THE CANADIAN LIGHT SOURCE

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## Abstract

During the injection process at the Canadian Light Source (CLS), approximately one third of the electron beam is lost from the Booster Ring (BR) to the Storage Ring (SR) at controlled locations in the Booster-to-Storage Ring (BTS) transfer line. In 2021, the BTS was upgraded to allow the facility to run in Top-Up mode. Included in this upgrade was the installation of new diagnostic CCD cameras in the transfer line with the intent to use them to measure beam properties and better understand the electron beam extracted from the BR.

This paper presents emittance measurements, using these diagnostic cameras, of the electron beam extracted from the BR. Using two quadrupoles, one focusing and one defocusing, quadrupole scan measurements were performed to measure both the horizontal and vertical emittances in the BTS. An estimated emittance in the BR was also measured using a combination of images of the synchrotron radiation produced by the BR and betatron functions, dispersion, and energy spread values obtained from simulations. These measured emittances were then compared to expected theoretical emittances of the BR from synchrotron radiation integrals.

## INTRODUCTION

In 2021, the BTS was upgraded such that Top-Up mode could be run at the CLS. During the upgrade, new diagnostic cameras and screens were installed in the BTS that allowed us to look at the beam in the transfer line. One of these diagnostic setups was placed early in the BTS transfer line after a pair of quadrupoles such that quadrupole scans could be done to measure the horizontal and vertical emittances of the electron beam extracted from the BR.

Emittance is a measure of the beam size in phase space coordinates. It is used as a metric of beam quality where a smaller emittance is typically preferred. If the electron beam extracted from the BR has a much emittance than expected, it could be part of the reason for the losses experienced in the BTS transfer line.

The emittance used in this paper is defined as [1–3]

$$\epsilon^2 = \sigma_{11}\sigma_{22} - \sigma_{12}^2 = \langle x_i^2 \rangle \langle x_i'^2 \rangle - \langle x_i x_i' \rangle^2, \quad (1)$$

where the  $\sigma$  components come from the  $\sigma$  matrix

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}. \quad (2)$$

The Twiss parameters contained within the  $\sigma$  matrix pro-

vide information about the beam, including position and momentum distributions.

## QUADRUPOLE SCANS

Quadrupole scans are a common method of measuring beam emittance [1–4]. Using the sigma matrix together with the transport matrices  $M$ , the propagation of the beam profile can be described by [1]

$$\sigma(s_1) = M(s_1|s_0)\sigma(s_0)M(s_1|s_0)^T, \quad (3)$$

which expands into the quadratic equation

$$\sigma_{1,11} = \sigma_{0,11}M_{11}^2 + 2\sigma_{0,12}M_{11}M_{12} + \sigma_{0,22}M_{12}^2. \quad (4)$$

When changing a quadrupole's strength, the beam shape can be seen changing on a view screen. Figure 2 is an example using a focusing quadrupole. These changes in horizontal and vertical beam sizes are then measured by calculating the  $1\sigma$  of the respective distribution. The relation between quadrupole strength and  $1\sigma$  beam size squared  $\sigma_{1,11}$ , (also referred to as variance) is then plotted and the  $\sigma$  matrix values can be obtained by fitting the data to Eq. (4), as shown in Fig. 1. Then the emittance can be calculated using Eq. (1).

Two Dimensional Quadrupole Scan  
 Horizontal Emittance = 579.214 nm

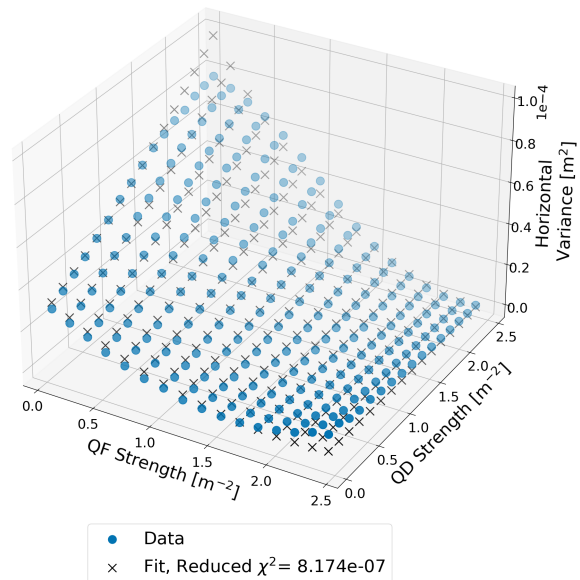


Figure 1: Horizontal variance plotted against focusing quadrupole (QF) strength and defocusing quadrupole (QD) strength, with a fit of the data to calculate horizontal emittance.

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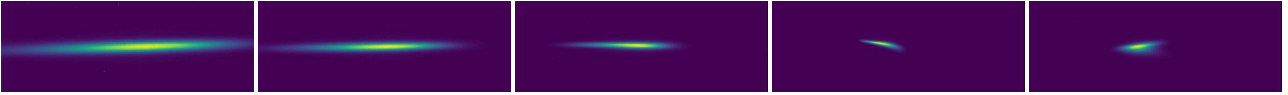


Figure 2: Changes in the beam due to varying the magnetic strength of a focusing quadrupole observed on the YAG screen as imaged by the CCD camera.

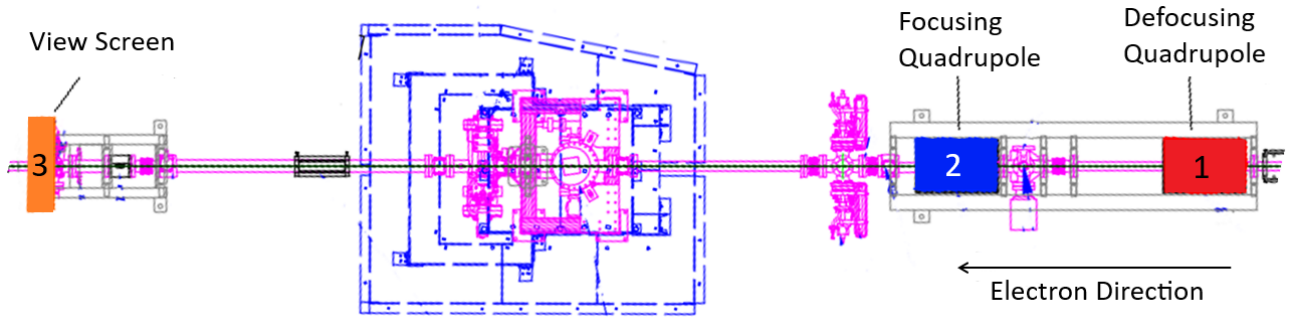


Figure 3: The section of the transfer line used for the experiment. Image modified from CLS drawing of the BTS [5].

## EXPERIMENTAL SETUP

The measurements were done early in the transfer line, as close to the Booster Ring as possible. The section of the accelerator chain used is shown in Fig. 3 with the electron direction depicted with the black arrow. First for the electrons there is a defocusing quadrupole, shown as a red rectangle with the number 1. Next is a focusing quadrupole, indicated with a blue rectangle and the number 2. The electrons strike a view screen, shown with an orange rectangle and the number 3, a few meters downstream of the focusing quadrupole. The camera is located on the inboard side of the transfer line looking into the vacuum chamber, which is topside in Fig. 3, looking at the screen through a view port as seen in Fig. 4.

There are two screens on rails at the view screen location that can be placed in the path of the beam; a phosphor, shown in the top of Fig. 4 and a yttrium aluminum garnet (YAG), shown in the bottom of Fig. 4. The phosphor screen was used for pixel to meter conversions, as it has millimeter markings on it. For the beam image acquisition, the YAG screen was used.

## SIMULATIONS

### Equilibrium Emittance

An equilibrium emittance is obtained in a circular accelerator when there is an equilibrium established between excitations and damping occurring in the beam. The theoretical horizontal equilibrium emittance assumes no coupling, and is a lower limit estimate of the horizontal emittance. The equilibrium emittance is calculated using [2, 6]

$$\epsilon_x = \frac{C_q \gamma^2 I_5}{I_2 - I_4}, \quad (5)$$

where  $C_q$  is a quantum fluctuation coefficient for electrons, equal to  $3.83 \times 10^{-13}$  m [2, 7] and  $\gamma$  is the relativistic Lorentz factor. The second, fourth, and fifth synchrotron radiation integrals are represented by  $I_2$ ,  $I_4$ , and  $I_5$  respectively.

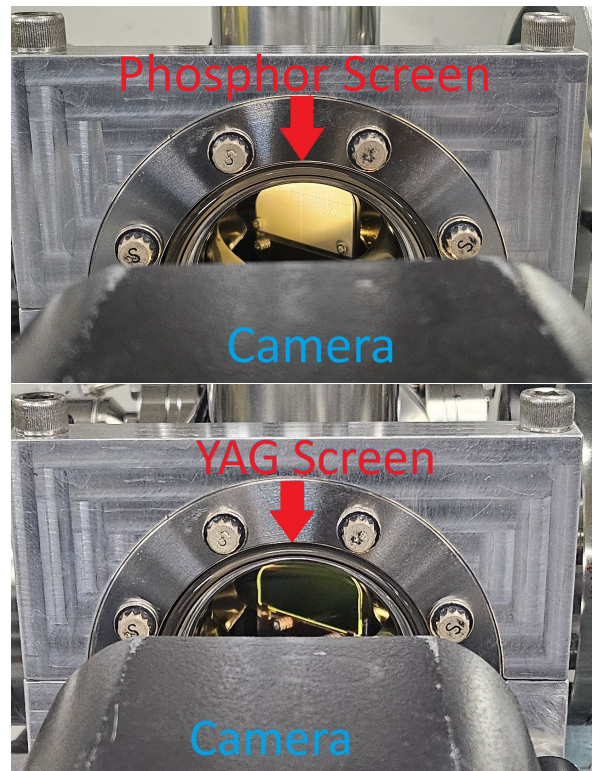


Figure 4: Images of the CCD camera (encased in black box) looking towards the view port into the vacuum chamber at the phosphor screen (top) and YAG screen (bottom).

To obtain the synchrotron radiation integrals, elegant [8] was used with a build of the CLS Booster Ring [9, 10].

The equilibrium emittance for the CLS Booster Ring was calculated to be 551.6 nm.

### BR Synchrotron Images

A relation between electron beam transverse bunch size and emittance can be written as. [11]

$$\epsilon_i = \frac{\sigma_i^2 - (\eta_i \sigma_\delta)^2}{\beta_i}, \quad (6)$$

where  $i$  is  $x$  for horizontal or  $y$  for vertical.  $\sigma_i$  is the electron beam size,  $\beta_i$  is the betatron function at the electron beam location,  $\epsilon_i$  is the emittance of the electron beam,  $\eta_i$  is the dispersion at the beam location, and  $\sigma_\delta$  is the fractional energy spread of the electron beam. The values of  $\beta_i$ ,  $\eta_i$ , and  $\sigma_\delta$  for this calculation were obtained from the same elegant simulation of the Booster Ring that was used in the previous emittance calculation.

The CLS has three cameras around the Booster Ring that are used to image the synchrotron light produced. One of the cameras is placed right before the point of extraction from the Booster Ring, and the image shown in Fig. 5 was taken slightly before the moment of extraction. These images were used to get an estimate of the electron beam bunch size.

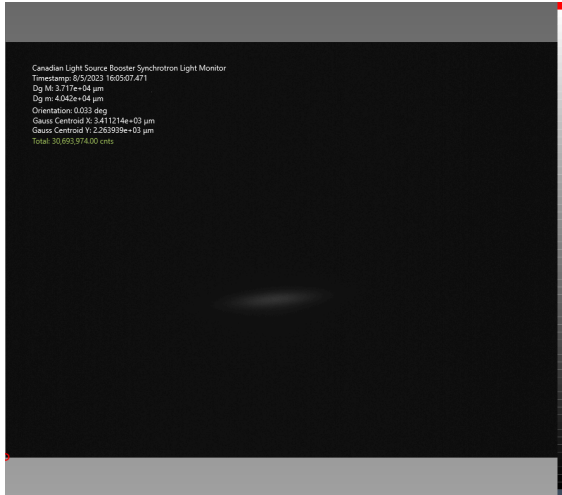


Figure 5: Image of the synchrotron radiation produced by the Booster Ring used to calculate estimated emittances.

Using the beam sizes measured from the synchrotron light image, by obtaining the  $1\sigma$  from a Gaussian fit, an estimated horizontal emittance of 476.9 nm and vertical emittance of 12.6 nm were calculated. This value is an estimate due to the uncertainties in the values of the Twiss parameters in the Booster Ring.

## RESULTS

Table 1: Table of emittances calculated with the different methods.

Method	Plane (nm)	$\epsilon$ (avg.) (nm)	std. dev.	# of meas
Quad. Scan	Horiz.	560.1	27.5	3
Quad. Scan	Vert.	16.4	4.5	3
Simulation	Horiz.	551.6	N/A	1
BR Sync.	Horiz.	476.9	N/A	1
BR Sync.	Vert.	12.6	N/A	1

Table 1 shows the number of measurements taken, the average of the measurements, as well as the standard deviation of the measurements. The average measured horizontal emittance of 560.1 nm is within 2% of the theoretical horizontal equilibrium emittance calculated of 551.6 nm, and

about 11-23% larger than the estimated emittance measured from the synchrotron images. The average measured vertical emittance of 16.4 nm is 1-3% of the calculated horizontal emittance and within the range of the estimated vertical emittance measured with the synchrotron light images.

Before the 2D raster scans scripts were developed, 1D quadrupole scans were done. They give results that do not agree to the same extent. To keep to the page limit, we had to limit the data presented here. The 2D data was chosen because it has approximately a factor of 10 more data points to fit to Eq. (4), as well as it calculates the emittance and Twiss parameters at the location of the first quadrupole for both the vertical and horizontal directions, whereas the 1D data gives the results at the beginning of the individual magnet used in the scan. For the full data set, please refer to [12].

## SUMMARY

The horizontal and vertical emittances of the electron beam extracted from the Booster Ring into the BTS transfer line were successfully measured with 2D raster scans utilizing both a focusing and defocusing quadrupole. Additionally, estimated horizontal and vertical emittances were measured in the Booster Ring using images of the synchrotron radiation produced in the Booster Ring.

The measured horizontal emittance in the BTS is within reason compared to the theoretical horizontal equilibrium emittance calculated using simulated values. The vertical emittance is a few percent of the horizontal, which is expected [13]. The emittances being close to simulation values indicates that it does not appear to be the cause of the losses in the BTS transfer line during injection.

## ACKNOWLEDGMENTS

We would like to thank the CLS Operator group for their assistance in collecting the data. This work is comprised of parts of C.-L. Randall's thesis [12].

The Canadian Light Source receives funding from the Canada 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.

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