

CHARACTERISATION AND OPTIMISATION OF THE DIAMOND LINAC IN PREPARATION FOR THE DIAMOND-II UPGRADE

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Abstract

The existing 100 MeV linac at the Diamond Light Source will be used as the pre-injector into the upgraded Diamond-II booster ring for injection into the new 3.5 GeV storage ring. In preparation for the upcoming upgrade, we have characterised the linac beam properties, to provide an input for beam tracking simulations and to optimise the linac beam dynamics. We present the latest linac performance results, the optimisation of the linac and linac-to-booster beam transport and the injection efficiency into the current Diamond booster ring.

INTRODUCTION

Diamond Light Source makes use of a 100 MeV electron linac pre-injector containing two identical 5.2 m-long accelerating structures, together with a three-stage bunching section and a 90 keV thermionic electron gun [1, 2]. The existing linac will continue to be used as a pre-injector into the upgraded Diamond-II booster ring for injection into the new 3.5 GeV storage ring [3]. In preparation for the Diamond-II upgrade, the beam dynamics in the linac and in the first section of the linac-to-booster (LTB) transfer line has been studied to develop the tools to achieve and maintain a high injection efficiency into the booster ring.

SUB-HARMONIC PRE-BUNCHER

The master oscillator frequency at Diamond is 500 MHz, which is the operating frequency of the radiofrequency (RF) cavities in the booster and storage rings. The linac gun and the sub-harmonic pre-buncher (SPB) that follows it are also operated at 500 MHz to produce either a single bunch or a train of bunches to be injected into the booster and then storage ring [4]. The remaining RF structures in the linac, comprising two bunching units followed by two accelerating structures, are operated at 3 GHz.

Operation of the SPB is not essential to inject beam into the booster; however, operating without the SPB results in the acceleration of around three 3 GHz ‘bunchlets’ along the linac for each 500 MHz pulse from the gun (Fig. 1a). These bunchlets have different beam trajectories and energy at the end of the linac, as can be seen on the beam charge distribution observed on screens in the LTB. For measurements involving the analysis of beam screen images (for example, for the emittance measurement described below), the SPB was turned on, and its power and phase was adjusted to obtain a single bunchlet (Fig. 1b).

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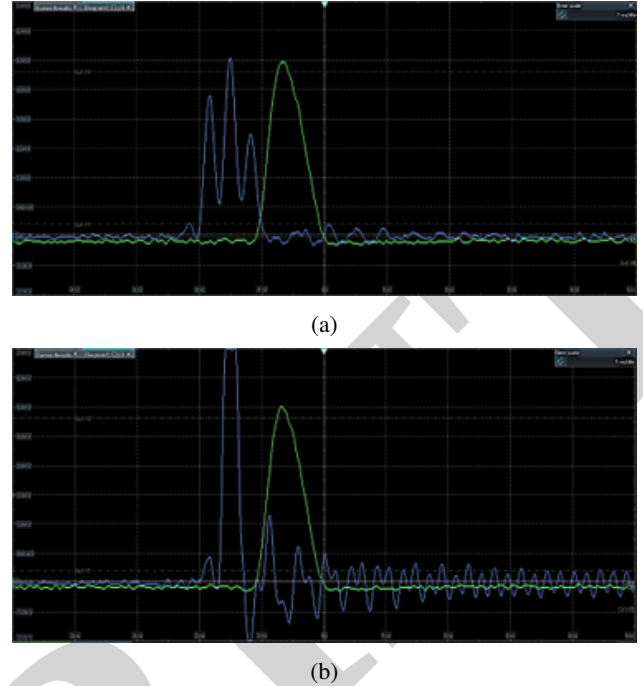


Figure 1: Wall current monitor oscilloscope traces showing bunch charge as a function of time with (a) SPB off and (b) SPB on, as measured upstream of the SPB (green) and at the end of the linac (blue).

HYSTERESIS CHARACTERISATION

Hysteresis is a known feature of the Diamond magnets due to their iron yokes. The established procedure is to cycle the magnets before setting the desired current. As the corrector magnets and quadrupoles in the LTB (Fig. 2) are on bipolar power supplies operated in the range of -5 A to 5 A, the cycling consists in following the sequence of magnet currents: 5 A $\rightarrow$ -5 A $\rightarrow$ 4 A $\rightarrow$ -3 A $\rightarrow$ 2 A $\rightarrow$ -1 A $\rightarrow$ 0 A. With a wait time of up to 15 s at each setting, the cycling takes close to 2 minutes.

We investigated if a reproducible magnetic field could be obtained for the first horizontal and vertical corrector (STR-01) and the first two quadrupoles (QUAD-01, QUAD-02) in the LTB without performing a full cycling procedure, by performing a beam-based measurement using a downstream beam position monitor (BPM). A step change in corrector or quadrupole setting from 5 A to -5 A results in a significant change in beam position at BPM-02; it was found that it takes ~ 1.4 s for the BPM reading to settle on its new value suggesting that a wait time of 2 s is sufficient for both correctors and quadrupoles in the LTB.

The hysteresis loop of STR-01 was mapped out by first fully cycling the corrector to 0 A and then varying the current

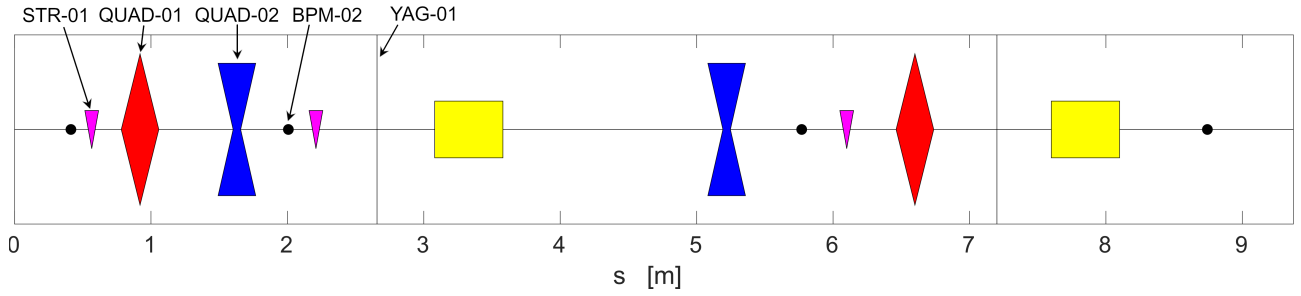


Figure 2: Lattice layout at the start of the LTB as a function of the distance travelled by the beam from the end of the linac (s), containing corrector magnets (magenta triangles), dipoles (yellow rectangles), horizontally-focusing quadrupoles (red diamonds), horizontally-defocusing quadrupoles (blue bow ties), BPMs (black circles) and screens (vertical lines).

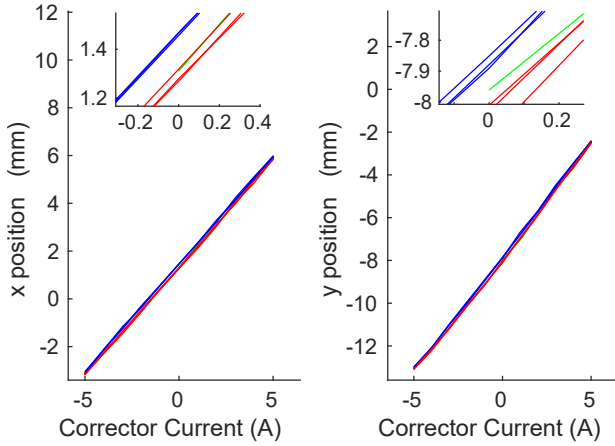


Figure 3: Position of beam at BPM-02 as a function of (left) horizontal corrector HSTR-01 and (right) vertical corrector VSTR-01 whilst varying the corrector current from 0 A to 5 A (green), from 5 A to -5 A (blue) and from -5 A to 5 A (red). The insets show a zoomed in portion of the scan.

in equally spaced intervals between the minimum and maximum in the following sequence: 0 A $\rightarrow$ 5 A $\rightarrow$ -5 A $\rightarrow$ 5 A $\rightarrow$ -5 A $\rightarrow$ 5 A $\rightarrow$ -5 A $\rightarrow$ 5 A. QUAD-01 and QUAD-02 were turned off to avoid additional steering. At each corrector setting the centroid of the beam was measured using BPM-02, averaging the beam position across 10 consecutive shots. Figure 3 shows the results of the measurements. The green line shows the initial increase in current from 0 A $\rightarrow$ 5 A. The blue lines show the times that the current was being decreased from 5 A $\rightarrow$ -5 A and the red lines show when the current was being increased from -5 A $\rightarrow$ 5 A.

The hysteresis in the quadrupoles was measured by first using the STR-01 to offset the beam in the quadrupole so that some steering is provided by the quadrupole, and then varying the strength of the quadrupole so that the amount of steering it provided was varied. A measurement was taken for each quadrupole and for each measurement, the strength of the quadrupole not being scanned was set to 0 A.

The strength of the quadrupole was changed in the same sequence as was done with STR-01. The centroid of the beam at BPM-02 was measured at each interval. Figure 4 shows the results of the measurement for QUAD-02.

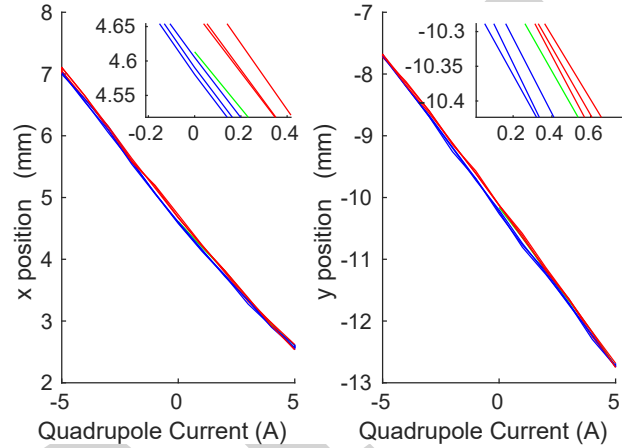


Figure 4: (left) Horizontal and (right) vertical beam position of beam at BPM-02 as a function of quadrupole current QUAD-02 whilst varying the quadrupole current from 0 A to 5 A (green), from 5 A to -5 A (blue) and from -5 A to 5 A (red). The insets show a zoomed in portion of the scan.

Both Figs. 3 and 4 show a distinct gap between the blue and red lines, showing that the steering strength of the magnet at a particular current was different depending on if it was being approached from a higher, or lower current. On the contrary, the traces of any given colour closely agree with other traces of the same colour, to within the shot-to-shot beam position jitter, suggesting that it is sufficient to obtain a reproducible magnetic field by, for example, always approaching the setpoint from a more negative setting. If a more negative setting is desired, the magnet can be set to 5 A, then -5 A and then to the desired setting.

K-VALUE CHARACTERISATION

A beam-based measurement of the k -values of QUAD-01 and QUAD-02 has been performed. Each quadrupole was scanned in turn; the quadrupole not being measured was cycled to 0 A. For the horizontal scan, STR-01 was set to I_{x0} , which resulted in the beam travelling through the centre of the quadrupole being measured.

The quadrupole being measured was cycled to 0 A. The current in the corrector was varied between -5 A and 5 A and the centroid of the beam at BPM-02 was recorded at each current. A straight line was fitted to this data. The y -intercept

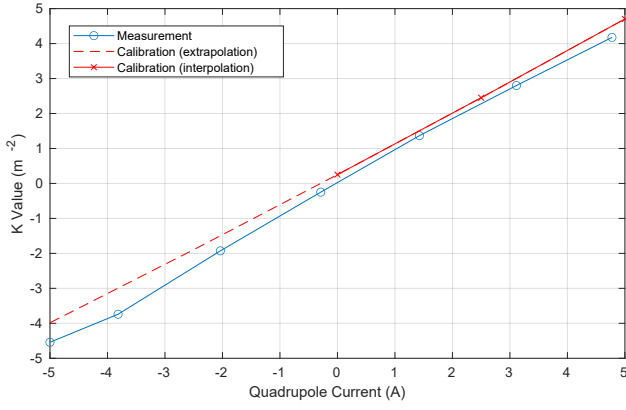


Figure 5: Measured QUAD-02 k-value as a function of quadrupole current, as calibrated prior to installation (red line) and as measured using beam (blue circles). The crosses and circles indicate measurements, solid lines are obtained by interpolating the data points and the dashed line by extrapolation.

of the fit-line was the BPM offset (x_0), and the gradient was used to calculate a calibration factor (C_x), which related the current in the corrector, to the angle (p_{x0}) that the beam exited the corrector such that:

$$p_{x0} = C_x(I_x - I_{x0}). \quad (1)$$

The quadrupole was turned back on, and set to a particular current. The current in the corrector was varied between -5 A and 5 A and the BPM positions were recorded. Using transfer matrices, it can be shown that the position of the beam at the BPM (x_{BPM}) with the quadrupole turned on follows the relationship:

$$x_{\text{BPM}} = p_{x0}(\mathbf{R}_{11}L_{cq} + \mathbf{R}_{12} + L_{qb}(\mathbf{R}_{21}L_{cq} + \mathbf{R}_{22})) + x_0, \quad (2)$$

where L_{cq} is the distance between the corrector and the start of the quadrupole, L_{qb} is the distance between the end of the quadrupole and the BPM and $\mathbf{R}_{mn}$ is the mn element in the transfer matrix of the quadrupole, which is a function of its k-value [5]. A numerical fitting routine was used to find the k-value that resulted in the best fit between the measured data and equation 2. The process was repeated with the different quadrupole currents.

A measurement was taken in both the horizontal and vertical planes. Initially, the calculated k-values in each plane did not match. This was likely due to some residual non-zero field in the quadrupole when the calibration factors (C_x , C_y) were measured. Due to the shape of the field in a quadrupole, the residual field caused an underestimate of the calibration factor in one plane, and an overestimate in the other.

A numerical minimiser was used to vary the calibration factors to minimise the difference between the calculated k-value in the x and y plane. The new calibration factors were used to calculate the k-values. The results can be seen in Fig. 5. They are plotted alongside the default calibration curve that was generated before the quadrupoles were installed over 20 years ago. This calibration was obtained using a unipolar power supply; the strength of the quadrupole

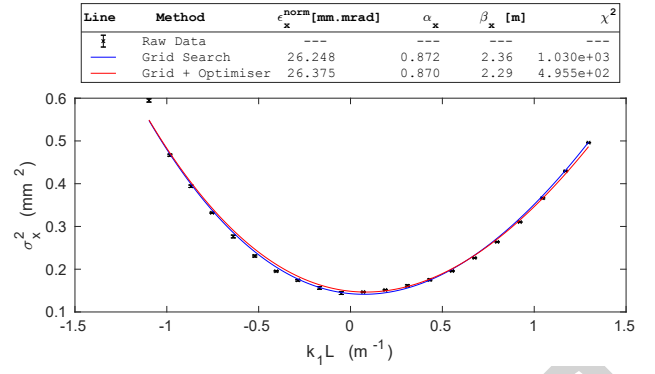


Figure 6: Measured σ_x^2 as a function of QUAD-01 kL , where $L = 0.275$ m is the length of the quadrupole. A grid search of possible ϵ , α , β is used to identify the grid point with the smallest χ^2 (blue line); this is used as an input to an optimiser which returns the red line.

at negative currents have been obtained by extrapolation. A difference can be seen between the calibration curve and the measured k-values. Further work is required to determine if this difference is real or whether it is affected by hysteresis and BPM nonlinearities.

EMITTANCE MEASUREMENT

The emittance ϵ and Twiss parameters α , β at the start of the LTB have been measured by scanning either QUAD-01 or QUAD-02 in the LTB and measuring the horizontal and vertical beam size (σ_x , σ_y) on the scintillator screen (YAG-01). Plotting σ_x^2 and σ_y^2 as a function of the quadrupole k-value gives a parabola in the thin-lens approximation [6, 7]. We have adapted the equations to use the thick-lens formulae. A numerical fit was used to find the values of ϵ , α , β at the start of the LTB which result in the best fit between the measured beam sizes and the equations.

The scan of QUAD-01 to measure σ_x^2 is shown in Fig. 6. In order to have a symmetric scan, with the smallest beam size at $k = 0$ for the scanning quadrupole (QUAD-01), the other quadrupole (QUAD-02) was set to a non-zero value. The actual emittance and Twiss parameter values differ by over a factor of two depending on the quadrupole being scanned which means that the measurements of ϵ , α , β are unreliable at present. Work is ongoing to understand the discrepancy by incorporating the results of hysteresis and k-value characterisation into the emittance scan measurements.

FUTURE STEPS

With the goal of characterising and optimising the beam dynamics in the linac and LTB in preparation for Diamond-II, we are planning to use the measured linac emittance and Twiss parameters to optimise the optics along the LTB. This will maximise beam transmission along the LTB and injection efficiency into the booster, for example, by reducing the dispersion throughout the LTB. As part of this effort, we are developing new commissioning tools for the linac and LTB, including tools for energy spread measurement, magnet beam-based alignment and LTB trajectory correction.

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