# STORAGE RING INJECTOR DIAGNOSTICS USING SYNCHROTRON RADIATION

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### *Abstract*

The state of the Diamond injector can be passively monitored using beam profile measurements of synchrotron radiation from bending magnets. This provides us with information on the characteristics of the beam injected into the storage ring. Using a numerical fit we are able to retrieve key parameters like beam position, size and tilt angle from every injection. This enables us to gather longer term trends to monitor for any changes during top-up operation and also to better understand any variability of the injector.

We present here the study and the analysis performed with this diagnostic with the results from several months of operation.


## OVERVIEW

During top-up operation, the injection efficiency needs to be monitored and maintained as close to 100% as possible. The main two reasons for this is to maintain low integrated radiation dose and to inject the top-up charges in the shortest time possible. One of the aspects of monitoring the injection efficiency is to observe the status of the injector. Together with the usual set of diagnostics such as scintillator screens and beam position monitors (BPMs), we have set up two synchrotron light monitors (SLMs) in the last two bending magnets of the Diamond injector.

Similar to BPMs, SLMs are monitoring the injected electron beam non-destructively and return beam position, however like the destructive OTR measurement they they carry the additional information of the beam size. Unlike the BPMs, the position information gathered by these two SLMs is relative to the image centre rather than the beam pipe. Further work will be needed to harmonize the reference points.

Using the SLMs, any change of the injector operation point will be visible immediately. Also long term monitoring of the injector beam size at injection is then available.

Beam size is a function of 4 parameters, the betatron and the dispersion functions, the emittance, and the relative energy spread. Position in dispersive sections such as bending magnets is strongly correlated with beam energy. Therefore the combination of the two SLMs might open the possibility to monitor all of these parameters. However, because the system of equations giving positions and beam sizes is under determined, it is not possible to find a unique solution. Nevertheless, by using a numerical model of the injector, it might be possible to isolate some particular cases where the diagnostic can reveal what and by what amount each parameter of the injector is deviating. In the following, we will firstly present the design of the SLMs. Then standard measurement of the dispersion and steering will show some of the expected behaviour of the beam. In addition we will show the stability of the injector over several weeks of observation. Finally, the dispersion and the beam size measurements will be compared to the model of the injector before discussing the development of this diagnostic.

To do the later we will combine the new data from the SLMs with other measurements and data from the theoretical model of the transfer path.

### *The Optical System*

In order to be sure that the magnification and alignment were correct, a mock-up of the final optical layout was assembled in the lab and the system was aligned using lasers. Field of view, magnification and depth of field were characterised using calibrated targets within precision of the order of 0.5%.

Once setup to specifications, the assembly was transferred to the machine as a unit, thus preserving the optical properties of the system.

The estimation of the resolution of the SLMs $\sigma_0$, taking into account the geometry and the source moving along the arc is 0.8mm and 0.1mm in the horizontal and vertical axis respectively[1].

### *The Image Analysis*

For each injection or top up cycle, images from many shots are captured and analysed using a Levenberg-Marquardt based two dimensional fitting routine. This routine is implemented in python and initially fits a one dimensional Gaussian to the sum in each direction, then uses those results as starting parameters to a 2 dimensional Gaussian fit. Figure 1 shows a typical image and fit from the first SLM.

From this analysis we can obtain the position of the source point (relative to the image centre), the beam size, and the tilt of the beam for each image.

## ACTIVE MEASUREMENTS

To make better use of the long term trend data we need to be able to separate out the effects of energy change and trajectory change.

### *Dispersion*

An energy shift should show up as correlated movement on both screens with the relative movement between

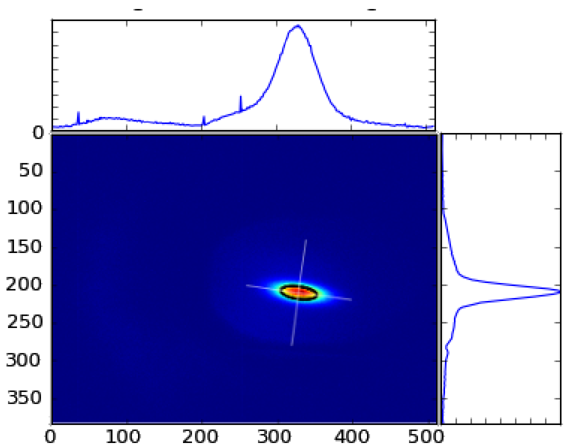


Figure 1: Example output of fitter on the first SLM position (Axes are shown in pixels).

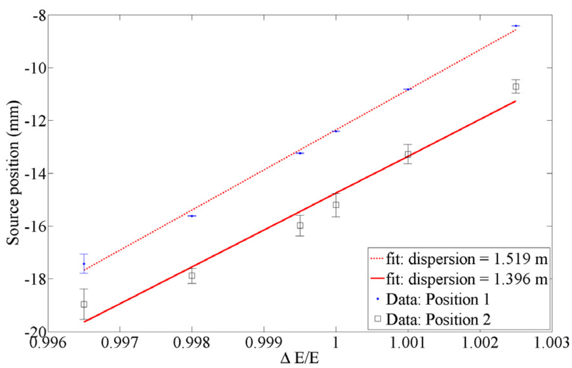


Figure 2: Example dispersion measurement.

screens governed by the dispersion at the two locations.

In order to find the dispersion values we ran a dedicated experiment where we changed the booster extraction energy and measured the change in position, with the dispersion being given by the gradient.

In our case the dispersion is very similar in the 2 positions so an energy shift should generate only a small differential movement between the screens but still show a correlated position shift (See Fig. 2).

### *Steering*

In order to verify that the SLMs can be used as BPMs, we adjusted the steering magnet which lies between the two source points in order to confirm that we have linear behavior and that there is no x/y coupling. Both x and y axes were swept in turn. The downstream SLM shows a linear trend with changing corrector magnet strength as expected (the error bars are shot to shot variation of the injector). The images also showed a very small reduction of the beam sizes (2% and 6%), indicating that the beam is probably not going through the centre of the quadrupole magnets. Figure 3

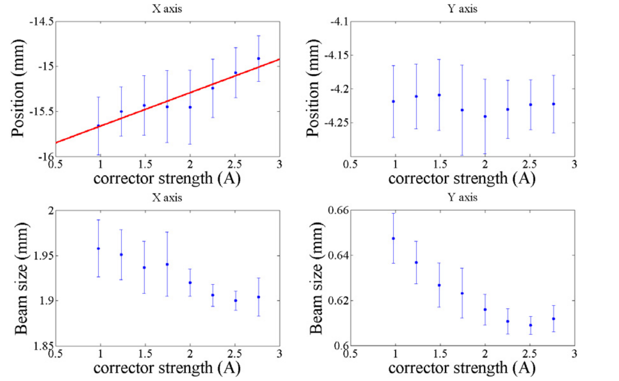


Figure 3: Position and size changes with horizontal corrector magnet strength changes.

shows a typical set of results.

## HISTORICAL TRENDS

Figures 4 and 5 show data from 4 periods of user time (blue), and three machine development slots (red).

Figure 4 is a plot of the movement of the source points over time, which clearly shows variations between the user runs. This is expected as the machine is tuned and improved during the machine development periods, however it is also clear that the injector is largely stable during the user runs. However, in several of the user periods there was a slow settling in the transfer path which took several days. It is hoped that with longer term data we could identify the sources of such drift.

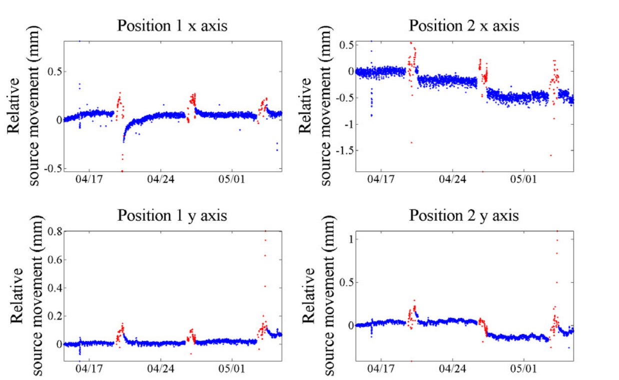


Figure 4: Position on both axes at the two SLMs over several user runs.

By using the new data on beam size we can distinguish between steering effects and focusing effects. Figure 5 shows very little change in the beam sizes within the four user periods so in this case it looks like any changes are mainly steering effects. By contrast a change in beam size is visible between user runs in the horizontal axis at position 2, when the injector optics were changed and matched to new storage ring optics.

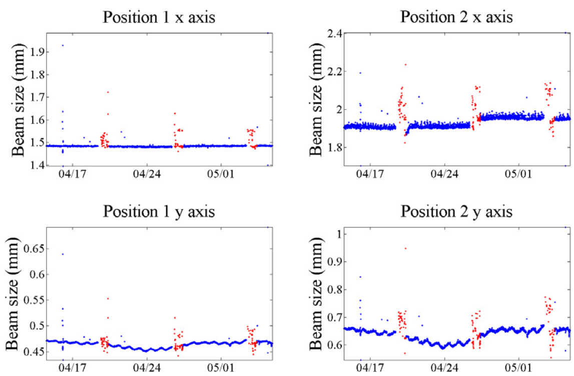


Figure 5: Beam size on both axes at the two SLMs over several user runs.

## FURTHER ANALYSIS

As we now know the dispersion $\eta$ and beam size at the source point $\sigma_x$, this allows us to calculate additional values which act to constrain our model of the transfer path further.

With the help of some additional information, the relative energy spread $\sigma_\epsilon$ from the model and previously done measurements of the emittance $\epsilon$ [2], it is possible to recover a value of the $\beta$-function at that position using:

$$\beta = \frac{\sigma^2 - \eta^2\sigma_\epsilon^2}{\epsilon} \quad (1)$$

However, the point spread function of the camera optics and of the source seen over the curved trajectory of the electrons has to be taken into account [1]:

$$\sigma_{corrected} = \sqrt{\sigma^2_{measured} - {\sigma_0}^2} \quad (2)$$

Table 1 shows all the corrected beam sizes as well as those predicted from the model. This indicates that further work is needed to bring the model and measurements into agreement. Generally the beam is measured to be smaller than expected in both locations, indicating stronger than expected focussing. The dispersion is lower as well by about 20%. A lower beam size would act to reduce the calculated $\beta$-function, while the reduced dispersion would increase it.

In our case the reduction in the beam size is dominant, and the measured horizontal $\beta$-function values are lower than from the model with the downstream position 2 reading showing a much larger discrepancy (47% vs 19%).

Table 1: Summary of Results

| | Position 1 | | Position 2 | |
|---|---|---|---|---|
| | Data | Model | Data | Model |
| $\sigma_x$ (mm) | 1.25 | 1.56 | 1.76 | 2.24 |
| $\sigma_y$ (mm) | 0.46 | 0.812 | 0.65 | 1.38 |
| $\eta$ (m) | 1.52 | 1.99 | 1.4 | 1.69 |
| $\beta_x$ (m) | 2.6 | 3.2 | 13.1 | 24.8 |
| $\beta_y$ (m) | 123.2 | 4.1 | 230.3 | 12.1 |

The predicted beam size and $\beta$-function depends on the precise knowledge of the position of the source, but also in the initial beam conditions at the entrance of the transfer line (corresponding to the booster extraction). This larger discrepancy can be explained by the fact that position 2 is located close after a beam waist therefore the $\beta$-function is rapidly increasing in the bending magnet. The position of this waist varies with changes to the booster extraction. This, combined with the rapid change in $\beta$-function makes position 2 much more sensitive to the differences between the machine and the model.

Estimation of the $\beta$-function in the vertical plane requires more careful study. In the first instance, a proper measurement of the SLM resolution is required, which has been so far estimated using known formulae. This is a prerequisite to the combined study of the vertical $\beta$-function and vertical emittance.

## FUTURE WORK

The next step is to use the data from the SLMs, along with data obtained from the optical transition radiation (OTR) screens to constrain the model.

Once we are happy that the model is showing a truthful result then we can begin interpreting the beam size variation. Equation 1 shows that the beam size depends on the $\beta$-function, the emittance and the relative energy spread. Once the model is refined we should be able to disentangle the effects of dispersion change, energy change and $\beta$-function change.

## CONCLUSIONS

The SLM system has been operating for many weeks, giving additional passively acquired data of the beam position and the beam size near the end of the injector. This has shown that the injector is fairly stable during user operation, however, there are distinct changes visible between user run periods. These changes are to be expected as the machine is tuned and adjusted and improved during these development periods.

For many uses the SLMs act as additional beam position monitors. However, the additional information on the beam size allows us to do more detailed characterisation at those locations. This in turn gives us more constraints to the model which, hopefully will lead to an improvement in the understanding of the whole transfer path.

## REFERENCES

[1] A. Hoffman, "Diagnostics with syncrotron radiation", CERN Accelerator School proceedings 2005.

[2] C. Thomas *et al.*, "Single Shot Emittance Measurement from Beam Size Measurement in a Drift Section", MOPE080, Proceedings of IPAC 2010.